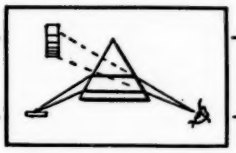
Journal of the OPTICAL SOCIETY *of* AMERICA

VOLUME 30
No. 7



JULY
1940

"Time to Stump the Experts" 275

Residual Photometric Errors in the Commercial Recording Spectrophotometer . . . . . ORRIN W. PINEO 276

Improved High Speed Recording Spectrophotometer . . . . . GEORGE R. HARRISON AND EDWARD P. BENTLEY 290

Production Color Analysis of Kinescope Screens . . . . . T. B. PERKINS 295

Erratum: Hue, Saturation, and Lightness of Surface Colors with Chromatic Illumination . . . . . DEANE B. JUDD 296

Complete Photoelastic Instrument . . . . . FRANK W. BUBB 297

Contrast Meter for Photographic Papers . . . . . C. A. MORRISON 299

Triboluminescence of Sugar . . . . . FRANCES G. WICK 302

Normal Systems with Two Caustic Lines . . . . . M. HERZBERGER 307

Optimum Efficiency Conditions for White Luminescent Screens in Kinescopes . . . . . H. W. LEVERENZ 309

Election of Officers 315

Research Notes:

Note on the Measurement of Pupillary Diameters . . . . . ROBERT C. HERMAN 316

On the Use of Oiled Photographic Emulsions . . . . . F. T. ROGERS, JR. 316

Necrology 317

Published monthly
at Prince and Lemon Sts., Lancaster, Pa.
by the
AMERICAN INSTITUTE OF PHYSICS
Incorporated
175 Fifth Avenue, New York, N. Y.
FOR AND UNDER THE EDITORIAL SUPERVISION OF
THE OPTICAL SOCIETY OF AMERICA

BOSTON UNIVERSITY
COLLEGE OF LIBERAL ARTS
LIBRARY

THE OPTICAL SOCIETY OF AMERICA

Officers of the Society

K. S. GIBSON, *President*
National Bureau of Standards
Washington, D. C.

A. G. WORTHING, *Vice President*
University of Pittsburgh
Pittsburgh, Pennsylvania

ARTHUR C. HARDY, *Secretary*
Massachusetts Institute of Technology
Cambridge, Massachusetts

HENRY F. KURTZ, *Treasurer*
Bausch & Lomb Optical Company
Rochester, New York

The Board of Directors consists of the above officers; the Editor of the Journal; the Past President; and five directors-at-large.

R. C. GIBBS, *Past President*
Cornell University
Ithaca, New York

GEORGE R. HARRISON, *Editor*
Massachusetts Institute of Technology
Cambridge, Massachusetts

Directors-at-Large

J. W. BEAMS
University of Virginia
Charlottesville, Virginia

H. P. GAGE
Corning Glass Works
Corning, New York

RUDOLF KINGSLAKE
Eastman Kodak Company
Rochester, New York

WILLIAM F. MEGGERS
National Bureau of Standards
Washington, D. C.

BRIAN O'BRIEN
University of Rochester
Rochester, New York

Rochester, New York, Section of the Optical Society of America

B. O'BRIEN, *President* R. B. HORSFALL, JR., *Vice President* D. L. MACADAM, *Secretary* J. W. GILLON, *Treasurer*
Councillors: H. F. KURTZ, J. H. MCLEOD, C. J. STAUD, T. R. WILKINS, R. E. BURROUGHS (*ex officio*)

Corporation Members of the Optical Society of America

AMERICAN OPTICAL COMPANY, Southbridge, Massachusetts
BAUSCH & LOMB OPTICAL COMPANY, Rochester, New York
BELL TELEPHONE LABORATORIES, INC., New York, New York
CORNING GLASS WORKS, Corning, New York
GAERTNER SCIENTIFIC CORPORATION, Chicago, Illinois
INTERCHEMICAL CORPORATION, New York, New York
KEUFFEL & ESSER COMPANY, Hoboken, New Jersey
SPENCER LENS COMPANY, Buffalo, New York
ARTHUR H. THOMAS COMPANY, Philadelphia, Pennsylvania

THE OPTICAL SOCIETY OF AMERICA was organized in 1916 "*to increase and diffuse the knowledge of optics in all its branches, pure and applied, to promote the mutual interests of investigators of optical problems, of designers, manufacturers and users of optical instruments and apparatus of all kinds and to encourage cooperation among them.*" It aims to serve the interests of all who are engaged in any branch of optics from fundamental research to the manufacture of optical goods.

MEMBERSHIP

Regular Members: "Any person who has contributed materially to the advancement of optics is eligible for regular membership."

Associate Members: "Any person who is interested in optics is eligible for associate membership."

Corporate Members: "Any corporation desirous of encouraging the work of the Society is eligible for corporation membership."

The Society cordially invites to membership all who are interested in any branch of optics, either in research, in instruction, in optical or illuminating engineering, in the manufacture and distribution of optical goods of all kinds or in physiological and medical optics.

ANNUAL DUES

Regular members, $7.50; Associate members, $5.00; Corporate members, $50.00. These dues include subscription to the Society's official journal, the *Journal of the Optical Society of America.*

MEETINGS

The Society holds two meetings per year: An annual meeting in the autumn and a midwinter meeting jointly with the American Physical Society.

All changes of address of members of the Optical Society of America should be communicated to the Secretary, Professor Arthur C. Hardy, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Journal of the
OPTICAL SOCIETY *of* AMERICA

VOLUME 30 JULY, 1940 NUMBER 7

"Time to Stump the Experts"

SCIENTIFIC publications, like individuals, are likely to grow increasingly conservative with age. This journal is no exception, and having passed its majority it can be expected to show both the good and the bad effects of receding adolescence.

Self-examination is salutary at all times, but is especially called for in times of stress. Perusal of the first twenty-nine volumes of this journal reveals that in the earlier issues the material it contained was far from stereotyped. Gradually, as the Optical Society of America and its journal have grown older and the average age of its members has increased, the material published has become more specialized, more detailed, and more specific. These qualities are necessary and desirable, but they should not be developed at the expense of the best interests of younger workers in optics, who are entitled to expect a certain proportion of general papers covering broad fields of optical information.

Wishing to correct this situation, and as a member of the scientific body-politic to respond to the present world emergency, the Journal believes that it can make a useful contribution by giving increased space, not merely to information, but also to the need for information. One of the principal services which a general article can render the reader is to recount not merely the present state of development of some field such as microscopy, interferometry, or spectroscopy, but also something of the limitations and needs of the field. The microscopist needs new lenses to use with ultraviolet light of extremely short wave-lengths; the lens designer is handicapped by lack of a rapid automatic ray-tracing machine; the spectroscopist would like to know how to make satisfactory replicas of large concave diffraction gratings; the telescope designer needs a photoelectric device to keep a photographic plate moving about to follow the jumping of star images. Many a random discussion of a lack or limitation has started a useful train of discovery or invention.

General survey articles on the topics listed above, as well as others, are now in preparation for succeeding issues of the Journal. In addition, to give the thoughtful reader an opportunity to air his needs and suggestions, the Editors will welcome brief communications citing instances of lacks in technique, apparatus, or information, which will be considered for publication as "Letters to the Editor." Now, as never before, it is "time to stump the experts."

The Twenty-Fifth Annual Meeting
of the
Optical Society of America
will be held in
Rochester, New York,
October 3, 4, and 5,
1940

BOSTON UNIVERSITY
COLLEGE OF LIBERAL ARTS
LIBRARY

Residual Photometric Errors in the Commercial Recording Spectrophotometer *

ORRIN W. PINEO
Calco Chemical Division, American Cyanamid Company, Bound Brook, New Jersey
(Received May 3, 1940)

The advantage of the spectrophotometer over the eye, in giving a quantitative record for future reference or interlaboratory comparison, cannot be utilized effectively in some applications unless its accuracy corresponds to the closest tolerances in direct visual comparisons. Although negligible for some purposes, errors due to stray light in the commercial recording spectrophotometer are significant by this criterion. Specific recommendations are given for reducing the individual sources of stray light and for compensating the remainders by adjustment of the photometric scale.

I. INTRODUCTION

GROWING interest in the commercial automatic recording spectrophotometer,[1] evidenced by the recent symposium sponsored by the Inter-Society Color Council and publication of its proceedings by the Optical Society of America,[2] appears to warrant a further review of some factors bearing on the photometric accuracy of the instrument.

As in visual color determinations which perforce are direct comparisons of similar color samples, two such samples can be directly compared one against the other in a spectrophotometer with a result giving particular and minute information on their difference, and only slight information on the general features which they have in common. The advantage of the spectrophotometer over the eye is not so much in its greater discrimination between samples in this application, as in its further applicability due to its quantitative evaluation of even large sample differences in terms having fundamental physical significance. In short, the advantage of the spectrophotometer is not so much that it does a finer job but that it does a different job.

Generally speaking, as the further applications of the spectrophotometer utilize its advantage in greater degree, the requirements for sensitivity, reproducibility and accuracy in its data are progressively more exacting.

For instance, the simultaneous comparison of similar samples, in mere substitution for visual comparison, involves (besides the ever-present considerations relating to the mode of mounting, illuminating and viewing the samples) merely the consideration of sensitivity alone, although a high order of sensitivity is required to equal the fine discrimination of the eye in this favorable sort of test.

Since the spectrophotometer can moreover evaluate large sample differences, it is possible and customary, when using the instrument, to compare separately each of the two similar color samples with a universal reference sample, and from the two similar results get information, not only on the difference between the samples, but also a specification of their common general features which relate them to all other samples. Successive comparison of each test sample with a universal reference sample in this way involves (besides considerations relating to the wide availability, permanence, and reproducibility of the reference sample) the further requirement that successive number-determinations be reproducible within such tolerances on the spectrophotometric plot as express the foregoing sensitivity requirement corresponding to the fine discrimination of direct visual comparison.

A further degree of utilization of the advantage of the spectrophotometer permits the remote comparison of color samples. This involves the further requirement that measurements made at widely different times or made on different instruments be reproducible within the same tolerances.

The advantage is utilized in final degree when the spectrophotometric data are interpreted in

* Contribution from the Physics Laboratory of the Calco Chemical Division (dyestuffs), American Cyanamid Company.

[1] Manufactured by the General Electric Company; described by Michaelson and Liebhafsky, "A new spectrophotometer and some of its applications," Gen. Elec. Rev. **39**, 445 (1936).

[2] J. Opt. Soc. Am. **10**, 360–397 (1938).

terms of the inherent physical color properties of a sample, as in identification of color constituents and estimation of their amounts. Whereas remote comparison of the superficial color properties of samples requires only that measurements be universally reproducible on any empirical scale of color value, objective analysis of samples introduces the further requirement that measurements be accurate on the fixed scale of some fundamentally significant quantity such as reflectance.

Consequently, the spectrophotometer has its most powerful and important use in preserving specifications of the inherent physical color properties of samples within tolerances corresponding to the limit of visual discrimination; and therefore it needs a high degree of sensitivity in discrimination and equal accuracy in presentation of data. The following will show that visual discrimination imposes a scale tolerance of around 1 percent of the reflectance value, which therefore is the maximum tolerance in photometric accuracy for this use of the instrument. Even when reproducibility would suffice for accuracy, a practical consideration is that in order to make a number of instruments permanently agree in their readings it is about as easy to remove as to standardize the stray effects causing any variations, and thereby attain accuracy at the same time. A deficient accuracy with adequate reproducibility will require a once-for-all calibration of each instrument by reference to known samples, while deficient reproducibility will require frequent calibration; since allowing for the calibration correction in every use of the data is very laborious, it should be obviated by adequate accuracy if at all possible.

For several reasons, photometric errors in transmission or reflection measurements will here be expressed as fractional errors in percentages of the measured (test sample) value, rather than as absolute errors in percentages of unit (reference sample) value; units of sensitivity, accuracy, and tolerances will correspond. On this basis, the photometric tolerances corresponding to visual discrimination are nearly constant throughout the range from white to black samples.[3] The same is true of the sensitivity of the recording spectrophotometer.[4] Finally, photometric tolerances are thereby made somewhat uniformly proportioned to tolerances in the inherent physical color properties of samples, such as concentration of color constituent. On the latter account, the following two examples of tolerances in dye strength testing have results largely independent of the particular samples used for illustration.

[3] This follows from the Weber-Fechner law.

II. Photometric Tolerances

Introductory to discussing the visual aspects of tolerances, the following remarks on two common color problems concern the economic aspects which sometimes are of primary importance.

In problems which involve adding color to a transparent material such as a dye solution, the transmittancy (Beer's) law leads to

$$d\mathbf{c}/\mathbf{c}=\frac{1}{\log_e \mathbf{t}}\cdot d\mathbf{t}/\mathbf{t},$$

where $d\mathbf{c}/\mathbf{c}$ is the fractional change in dye concentration or amount $\mathbf{c}$ corresponding to a fractional change $d\mathbf{t}/\mathbf{t}$ in the sample transmittancy[5] $\mathbf{t}$ at any given wave-length. To color makers and users, the fraction $d\mathbf{c}/\mathbf{c}$ of color strength is directly a fraction of the color cost which should be ascertainable to within a very few percent. A 1-percent strength tolerance, for instance, thus requires a 2-percent tolerance in $\mathbf{t}=0.15$ which is a representative value in dye strength testing.

In problems which involve adding color to a diffusing material such as a textile dyeing (or a paint), the reflectivity (Kubelka and Munk) law[6] leads similarly to

$$d\mathbf{c}/\mathbf{c}=-\frac{\mathbf{r}(1+\mathbf{r}-2\mathbf{s})}{(\mathbf{r}-\mathbf{s})(1-\mathbf{r})}\cdot d\mathbf{r}/\mathbf{r},$$

[4] This is purposely gained by the photo-cell coupling circuit described on pp. 105–106 of Hardy, "A recording photoelectric color analyzer," J. Opt. Soc. Am. **18**, 96 (1929). Note that Eq. (7) omits a factor $\log_{10} e$ and should read $dEg=0.1\ dIg/Ig$. See also Meagher and Bentley, "Vacuum-tube circuit to measure the logarithm of a direct current," Rev. Sci. Inst. **10**, 336 (1939).

[5] For the definition of terms relating to transmission and reflection see p. 177 of: "Spectrophotometry; Report of O. S. A. Progress Committee for 1922–23," J. Opt. Soc. Am. **10**, 169 (1925). Also p. 288 of Judd, "Optical specification of light scattering materials," J. Research Nat. Bur. Stand. **19**, 287 (1937).

[6] Kubelka and Munk, "Ein Beitrag zur Optik der Farbanstriche," Zeits. f. tech. Physik **12**, 593 (1931); errata, *ibid.* **13**, 101 (1932).

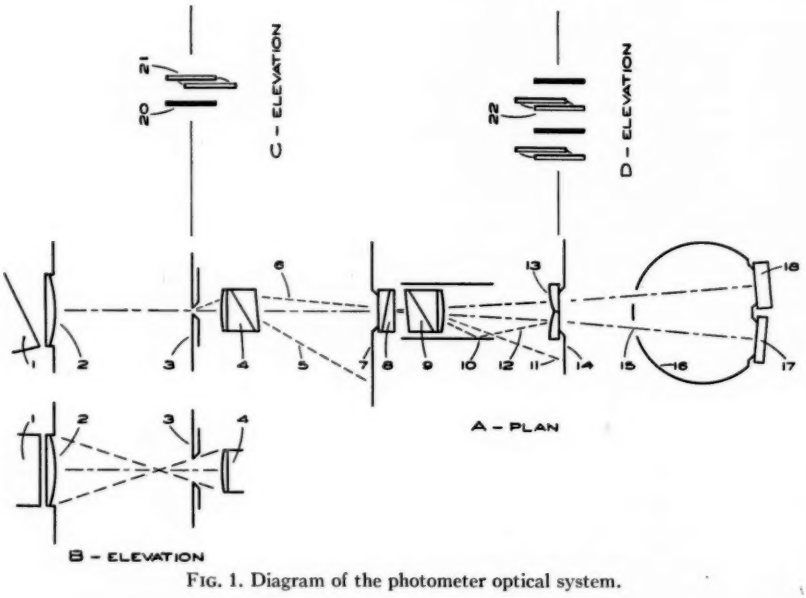


FIG. 1. Diagram of the photometer optical system.

where **r** is the measured total reflectance of the material at any given wave-length and **s** is the constant surface reflectance approached by **r** as **c** becomes large. Again, color strength is color cost and a similar 1-percent tolerance here requires a closer tolerance of $\frac{3}{4}$ percent in $r=0.05$ when $s=0.01$, a favorable case in dye strength testing.

Now considering some visual aspects, the dye tester can definitely see about a 4-percent strength difference by direct comparison of two textile (skein) dyeings similar to the one mentioned above. Thus a 3-percent reflectance tolerance corresponds to visual discrimination in color strength (color-quantity) comparisons. This result, in the case of achromatic or of very chromatic samples, is independently to be expected from the Weber-Fechner law and a photometric comparison field with considerable extent but poor dividing line. Where shade (color-quality) considerations are involved, the photometric field is more favorable and closer tolerances of 1 percent and less[7] may frequently, but not always,[8] be required to equal visual discrimination.

Therefore in a practical spectrophotometer, 1-percent photometric sensitivity is required for discrimination, together with equal accuracy for convenient, straightforward interpretation of data without reference to calibration corrections. The General Electric recording spectrophotometer has the required sensitivity on appropriate plots, but it will be shown that unless changes are made in the optical system and in the procedure for adjustment, photometric errors as large as ten or twenty percent can be caused by stray light.

III. Stray Light Errors

Illustrative example of diffraction and reflection by monochromator exit slit edges

A schematic diagram of the photometer optical system in plan view is shown at *A* in Fig. 1. Spectrum light[9] enters the system through the monochromator exit slit **3** and is polarized by the "photometer prism" **4** which deviates light of

[7] Park, "Color comparison devices," Am. Dyestuff Reporter **29**, 272 (1940).

[8] Nutting, "The detection of small color differences in dyed textiles," J. Opt. Soc. Am. **24**, 135 (1934).

[9] In the instruments examined by the author, the small range of wave-lengths comprised in this light was materially (5mμ in red) larger than might be expected from the sizes of the monochromator slits and spectrum, due to the fact that each of the four collimator lenses near the dispersing prisms was mounted with its convex surface away from the prism as shown at *2* in the figure, thereby introducing four times more spherical aberration than it would if reversed. Consequently, their spectral resolution was less than looked for and, in particular, checking their wave-length scale with a line source and narrowed slits was notably indeterminative.

unwanted polarization **5**. The wanted and unwanted polarizations are separated by stop **7** because the angle which the dispersing prism **1** subtends at the photometer prism lens is smaller than the angle of deviation. Some light, however, is so deviated by diffraction at the slit edges that its unwanted polarization is again deviated by the photometer prism to pass the stop, as represented by **6**. Furthermore, in the commercial instrument the slit edges are so broad that additional stray light is similarly deviated by reflection from one of them. In viewing slit **3** through the aperture in stop **7**, these stray beams appear as in Fig. 1-*C* to originate in a separate slit outline **21**, which is slightly displaced from and which rotates 45° about the stationary slit image **20** due to deviation in the rotatable photometer prism. After being doubled by the Wollaston prism **8**, the beams are doubled again by the "flicker prism" **9** but only the undeviated ones are passed by stop **14** where they form the slit images shown in Fig. 1-*D*. The stray image **22** associated with the reference beam is of maximum brightness when the reference beam itself reaches zero brightness or extinction because of its originally opposite polarization; but it has the same flicker variation with time so that, if it reaches the reference sample **18**, it produces an absolute error at low reflectance values equal to the original brightness ratio of **21** to **20** in Fig. 1-*C*. The stray image **22** appears in the center of the photograph, Fig. 2, between the images of the test beam on the left (nearly extinguished by means of the flicker prism **9**) and the reference beam on the right (nearly extinguished by means of the photometer prism **4**).

The amount of this stray light **6** is substantially independent of the slit width and can be estimated by visual comparison with the nearly extinguished reference beam. At the mean slit width for 10-millimicron purity,[10] the ratio of stray to wanted light is about 0.003. The width of the slit changes through the spectrum to maintain constant purity, changes the amount of wanted light, and thus varies the stray light ratio between limits of approximately 0.0012 and 0.0075 for 10-millimicron purity, and from 0.003 to 0.02 for 4-millimicron purity.[11] This stray light is thus capable of producing, in the instrument equipped for 10-millimicron purity, an absolute photometric error of 0.0075 at low values where it becomes very important.

The stray light **21** is widely separated from the wanted light **20** by virtue of the $1\frac{1}{2}$ inch separation between the slit and the photometer prism, but only at the cost of about three millimeters extra diameter of the photometer prism as shown in Fig. 1-*B*. Enough separation to place (as shown in Fig. 1-*D*) the stray image **22** between the wanted images, which alone were passed by stop **14**, was incorporated in the prototype spectrophotometer,[12] constructed at the Massachusetts Institute of Technology and used as the basis of the commercial instrument. The optical elements of the commercial instrument and their spacing are the same[13] as those of the

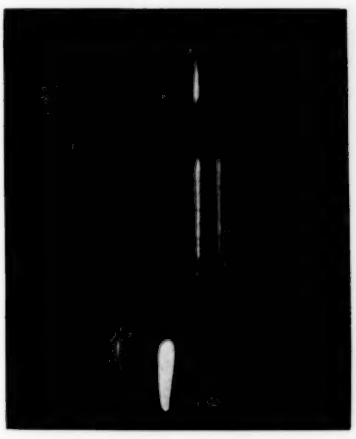


FIG. 2. Photograph of the image at stop **14**, Fig. 1-*A*; compare with Fig. 1-*D*.

[10] The value for which the commercial instrument is usually equipped, see p. 367 of Michaelson, "Construction of the General Electric recording spectrophotometer," J. Opt. Soc. Am. **28**, 365 (1938).

[11] The spectrophotometer so equipped has been supplied on special request. For comment on its use, see Gibson, "Calibration and operation of the General Electric recording spectrophotometer of the National Bureau of Standards," J. Opt. Soc. Am. **28**, 372 (1938).

[12] Hardy, "A new recording spectrophotometer," J. Opt. Soc. Am. **25**, 305 (1935).

[13] Hardy, "History of the design of the recording spectrophotometer," J. Opt. Soc. Am. **28**, 360 (1938). Other exceptions relate to the collimator lenses in the monochromator (see footnote 9) and to the monochromator entrance slit whose width in the commercial instrument (already one and a half times that of the exit slit, see Michaelson, reference 10, p. 367) should be more than doubled. Also, in connection with points to be mentioned below, the prototype instrument needed no microswitch; it had toric lenses at the photometer and flicker prisms; and finally, it had a different loglog cam and a different cam follower.

prototype instrument except that stop **14** passes all four of the beams shown in Fig. 1-*D*. The user of the commercial instrument can readily rectify this condition by properly applying at stop **14** two strips of black paper to eclipse the stray images.

Basic formulation of instrument operation neglecting stray light

The first-order effect, on which the second-order stray effects are superposed, is briefly described[14] by writing for L, the sum of energies reflected from the test and reference samples,

$$\begin{aligned} L &= \mathbf{r}(\omega t)\mathbf{t}(\omega t)[A(\alpha)\cos\alpha\cos\omega t]^2 \\ &\quad + \mathbf{R}(\omega t)\mathbf{T}(\omega t)[A(\alpha)\sin\alpha\sin\omega t]^2 \\ &= \tfrac{1}{2}A^2(\alpha)[\mathbf{rt}\cos^2\alpha + \mathbf{RT}\sin^2\alpha] \\ &\quad + \tfrac{1}{2}A^2(\alpha)[\mathbf{rt}\cos^2\alpha - \mathbf{RT}\sin^2\alpha]\cos 2\omega t, \end{aligned} \quad (1)$$

where $\mathbf{r}(\phi)$ and $\mathbf{R}(\phi)$, respectively the test and reference reflectances as a function of the angle of incident polarization, are here[15] considered constant independent of ϕ and so denoted by $\mathbf{r}$ and $\mathbf{R}$; where $\mathbf{t}$ and $\mathbf{T}$ are similarly the test and reference transmission; where $A(\alpha)$ is the amplitude of the wanted beam transmitted by the photometer prism as a function, due to polarization in the monochromator,[16] of the photometer prism azimuth, α radians, with respect to the Wollaston prism; and ωt is the similar azimuth of the rotating flicker prism. The first term on the right of the second equation can be associated with the constant photo-cell current, and the second term with the alternating photo-cell current which comprises the signal to be amplified. The photometer prism is driven by the amplified signal until at "balance" the signal vanishes and

$$\tan^2\alpha = \mathbf{rt}/\mathbf{RT} = r, \quad (2)$$

where r is the desired relative reflectance or transmission of test and reference samples.

When out-of-balance by amount dr, the alternating photo-cell current is proportional to $\mathbf{RT}dr/(1+r)$, the constant photo-cell current is proportional to $2\mathbf{RT}r/(1+r)$, and the input signal (see footnote 4) is 0.035 dr/r volts r.m.s. Conversely, any stray electrical signal in the amplifier will cause a photometric error (relative) which is independent of r. An error is indicated by a balance motor torque which causes the plotting pen to creep when the light is cut off. Its uncompensated magnitude is that of the photometric unbalance giving equal torque. It can be partially compensated, like the stray light errors below, but no further discussion will be given here because such would apply only to the present photo-cell coupling with logarithmic response.

Extended formulation including four types of stray light denoted by κ, λ, μ, ν

Equation (1) can be extended to include stray light sources in the system due to diffraction, diffusion by dirt, etc. In formulating these second-order effects, the variation of $A(\alpha)$ with α can be neglected for simplicity. One writes down the stray energies leaving the test and reference samples as follows, due to:

Diffraction and reflection by the monochromator exit slit edges as described above—

$$\kappa\mathbf{rt}[A\sin\alpha\cos\omega t]^2 + \kappa\mathbf{RT}[A\cos\alpha\sin\omega t]^2,$$

where κ is the mentioned stray light ratio, about 0.003.

Dirt on the photometer prism—for purposes of analysis, "dirt" may be resolved into two idealized components: (1) "dust" which diffuses and depolarizes, and (2) "grease" which diffuses by deviation without depolarization. For "dust" on the photometer prism,

$$\kappa'\mathbf{rt}A^2\cos^2\omega t + \kappa'\mathbf{RT}A^2\sin^2\omega t,$$

where κ' is the fraction of the light at the photometer prism which is depolarized and directed toward the opening in stop **7**. If κ' be carried separately through the derivation of the combined effects of the different types of stray light (Eq. (3) below), it will be found to enter symmetrically with stray light of type κ; therefore, it can be accounted for in an augmented value of κ. The same is obviously true of κ'', the fraction of the unwanted polarization **5** which is deviated to pass stop **7** as a result of "grease" on the photometer prism.

[14] A less condensed description of the first-order operation of the instrument is given by Hardy, p. 307 of reference 12.

[15] A more general case will be discussed in a later publication.

[16] For the present double monochromator, the ratio of energies $A^2(0)/A^2(\pi/2)$ equals $2\frac{1}{2}$ approximately, depending somewhat on wave-length setting. In the prototype and commercial instruments, the larger energy was made available for the measurement of dark samples, while at the same time the slit image **21**, Fig. 1, due to stray light diffracted at the monochromator exit slit was segregated by a side-wise displacement from the wanted image **20**. Thus the photometer prism actually used was somewhat different from the description given by Hardy on p. 308 of reference 12. In any design, available glasses permit only the ordinary ray in the calcite to be achromatized for rectilinear transmission, and the refracting angle of the glass element must be larger than that of the calcite element. See Pineo, "A modified Rochon prism" (abstract), J. Opt. Soc. Am. **23**, 117 (1933).

Dirt on the Wollaston and flicker prisms—"dust" produces a stray energy having no time variation and therefore contributing nothing to the alternating-current signal; for "grease,"

$$\lambda \mathbf{rt}[A \sin\alpha \sin\omega t]^2+\lambda \mathbf{RT}[A \cos\alpha \cos\omega t]^2,$$

where λ is the fraction of the test beam (respectively, reference beam) at the prisms which is deviated to pass through the wrong decentered lens and the stop **14**. This stray light can become quite large due to the formation on the Wollaston prism of a pinwheel-pattern of oil from the flicker motor bearing. It can be observed by examining with a lens[17] the beam at the reference sample **18** when the photometer is set for extinction of the beam. Inspection and cleaning of the Wollaston prism every two or three months is necessary to maintain $\lambda<0.001$. The flicker motor bearings should be oiled very sparingly with this in mind.

Diffraction by stop 7—a small effect accounted for by an increased value of λ.

Inexact Wollaston prism construction—producing at the mid-position near **22**, Fig. 1-*D*, a faint slit image which can be eclipsed together with **22** and its effect neglected. The crystal axes of the two halves of the Wollaston prism should be set at 90°; one prism showed on examination an error of 0.4 degree.

Reflection from wall of tube 10 as shown at 12 in Fig. 1—

$$\mu(\mathbf{t}+\mathbf{T})\mathbf{Q}\{[A \cos\alpha \sin\omega t]^2+[A \sin\alpha \cos\omega t]^2\},$$

where μ is the fraction of the unwanted polarization deviated by the flicker prism, which is reflected to pass through each of the decentered lenses and the stop **14**, to traverse any test or reference transmission samples, and to reach the sphere wall of reflectance **Q**. This stray light can be observed by looking through the stop **14** and decentered lens **13** toward the flicker motor, preferably with the help of a negative lens to neutralize the decentered lens; μ is found to be about 0.01, and is evidenced by the flare covering the center of Fig. 2. This analysis will show the desirability of reducing its value by a series of narrow diaphragms in tube **10** or by use of the "coffin" paper customarily employed for such purposes in optical instruments. Additional remedies will be mentioned below.

Imperfect stopping by the apertures in **14** and at **15** or by dirt on the decentered lenses **13**, *together with the first-order effect*, Eq. (1)—

$$(1-\nu)\mathbf{rt}[A \cos\alpha \cos\omega t]^2+\mathbf{RT}[A \sin\alpha \sin\omega t]^2,$$

where $(1-\nu)$ is the transmission of the test beam optics relative to that of the reference beam optics. The value of ν is usually 0.01 or less, but it will be proposed in a later publication to introduce purposely a large value to compensate, in some cases, the deficiency of **R** from unit reflectance. Dirt on the decentered lenses can also augment λ by diffusing part of the test beam into the reference beam and vice versa.

Oscillation of the images at stop 14—this is caused by the astigmatic imagery through the rotating asymmetrical flicker prism; it is conducive to the imperfect stopping discussed immediately above, in conjunction with which it introduces spurious signals at flicker frequency with consequent departure from correct balance. This astigmatism can be largely compensated by substituting a toric lens on prism **9** and carefully centering the combination.

Intersurface reflections from the various elements in the optical train—several can be observed, but their effect is mostly to produce signals at other than flicker frequency and they will here be neglected.

The above first-order and stray energies are added to give a signal which vanishes when

$$\tan^2\alpha=(1-\nu)r+(\lambda-\kappa)(1-r^2) -\mu(\mathbf{t}+\mathbf{T})(1-r)\mathbf{Q}/\mathbf{R},$$

neglecting third-order terms as will also be done below without further mention. Attention will be confined to the cases wherein a white reference sample and a white sphere are used, so that

$$\tan^2\alpha=r+\eta(1-r^2)-j\mu(1-r)^2-\nu r, \qquad (3)$$

where $\eta=\lambda-\kappa-\mu$. When measuring reflection samples, $j=1$; and for transmission samples, $j=0$. The distinction between η and $j\mu$ is merely that the former stray light strikes the sample and the latter the sphere wall. To reduce their total amount, the apertures at the decentered lenses and the entrance windows in the sphere should barely clear the beams, and a nonreflecting partition between the beams should extend all the way from the sphere to the decentered lens stop. Moreover, since $j\mu$ will prove to be the more troublesome it can advantageously be reduced at the cost of an increase in η by increasing the size of the reflection test sample window in the sphere. Finally, $j\mu$ can be reduced at the expense of wanted light, and hence of signal strength, by reducing the diameter of the sample illuminated spot (which is controlled by the stop at the Wollaston prism) or by reducing the height of the slit images at the decentered lenses (which is controlled by the height of the monochromator exit slit). In the design of the prototype instrument, a compromise of these geometrical considerations resulted in a negligible amount of stray light $j\mu$ reaching the sphere wall. An essential feature of the design was the use of a toric lens at the flicker prism to permit a smaller test beam entrance window by minimizing the oscillation of the beam. The size of the reference beam entrance window is not so important.

[17] Not to magnify, but to "collect" by focusing onto the observer's pupil the slit image at stop **14**.

Separate effects of the four types of stray light

Inspection of Eq. (3) shows the stray light ν to be the only one effective when the relative reflectance being measured is unity, and its effect on the "100-percent line" in this case is similar to that which would be produced by using a reference sample with higher reflectance **R**.

The three kinds of stray light summed in η are most effective on low measurements—λ tending to raise them toward the 100-percent line, κ and μ tending to depress them, the effect of μ being twice as great in reflection measurements as in transmission measurements. If the photometer be perfectly adjusted without reference to any stray light effects, then $\tan^2\alpha$ is the apparent r as given by Eq. (2), and the absolute error at low values is

$$\lambda-\kappa-(1+j)\mu.$$

Unless reduced in the manner mentioned, this sum for reflection measurements is around -0.02 which leads to relative photometric errors around -40 percent and to dye-strength errors larger than $+50$ percent in the textile example given above.

The presence of this stray light is strikingly demonstrated by another effect wherein the instrument is unable to balance very dark samples. Now $\kappa+(1+j)\mu$ is much larger than λ, and unless this excess tendency to depress the curve is more than counteracted by a sample reflectance greater than 0.02, the signal drives α to negative values where the driving force is *away from balance* and an unstable condition results. This difficulty in measuring very dark samples has been overcome in the commercial instrument by providing a microswitch to break the drive toward smaller α at a predetermined value of α. Thereby is drawn on the plot a smooth "zero line" which, however, has no reference to any sample and has no usefulness beyond indicating the proper adjustment of the plotting paper on the drum, etc. By one or more of the changes suggested, the user of the commercial instrument can easily reduce the sum $\kappa+(1+j)\mu$ until it is less than λ. (The sum $\kappa+(1+j)\mu$ is due to diffraction and reflection by the monochromator slit, dirt on the photometer prism, and reflection from tube **10**; λ is due to "grease" on the Wollaston and flicker prisms, diffraction by stop **7**, and diffusion by dirt on the decentered lenses.) Then the instrument not only balances a zero transmission sample at a real angle $\alpha=\sqrt{\eta}$ but returns to balance when it overshoots toward negative α by amounts up to $2\sqrt{\eta}$. Minimizing all the stray light as carefully as possible seems to leave λ predominant by an amount $\eta=+0.001$, giving four degrees allowable overshoot with stability; this condition of operation permits removal of the microswitch, and is believed to be otherwise desirable. At the same time, the reduced stray light causes the photometric and dye-strength errors just mentioned to be respectively -2 percent and $+3$ percent, which are not excessive but which nevertheless will be further reduced by compensation.

IV. Ordinate Plotting Mechanism Errors

Measurements have been made which indicate that the cams supplied with two of the commercial instruments have the proper profile to translate accurately the photometer prism azimuth α into the recording pen ordinate position r according to the first-order relation

$$\tan^2\alpha=r$$

as stated by Michaelson.[18] Two 100-percent cams and two 20-percent cams were checked. Observed deviations from the tangent-square law were ascribed to flat spots worn on the roller of the cam follower. It is to be noted that an infinite slope is prescribed for the cams at $r=0$, but the region of steep slope has been replaced in the actual cams by uniform spirals whose slope $d\alpha/dr$ was found by measurement to be 5 radians and 17.5 radians for the 100-percent and 20-percent cams, respectively. The slope of the 100-percent cam spiral was found to be that of the true tangent-square cam at $r=0.010$, at which point the two are assumed to be tangent and below which (as cautioned in the instruction folder) the 100-percent cam should not be used; the extinction setting $\alpha=0$ is computed[19] from this to be at $r=-0.010$. The extinction setting on the 20-

[18] Michaelson, reference 10, p. 368.

[19] By direct measurements the extinction setting was determined to be at $r=-0.009$. See Gibson, reference 11, p. 374.

percent cam has conveniently been made at $r=0.000$, and the spiral intersects the true cam at $r=0.003$ below which the 20-percent cam should not be used.

Means are provided for adjusting the datum azimuth of the photometer prism, nevertheless its azimuth α may inadvertently exceed that dictated by the cam design by a small additive angle β radians. A similar angle $i\gamma$ may be introduced by a flat spot on the cam roller, i being zero except when the flat spot is in contact with the cam thereby making $i=1$. Despite proper lubrication of the roller, its replacement several times a year is necessary to avoid flat spots more than 0.03 inch wide due to 0.002-inch radial wear on the 0.125-inch roller. For a spot of this size, $\gamma=0.001$ radian more or less independently of the cam slope. The value of r inferred from the cam radius at the follower when in balance is therefore

$$\begin{aligned}\text{cam } r &= \tan^2(\alpha-\beta-i\gamma)\\ &= \tan^2\alpha-(\beta+i\gamma)\frac{d}{d\alpha}\tan^2\alpha\\ &= r-2(\beta+i\gamma)r^{\frac{1}{2}}(1+r)\\ &\qquad +\eta(1-r^2)-j\mu(1-r)^2-\nu r\\ &= r+h \qquad (4)\end{aligned}$$

by introducing Eq. (3) and denoting the total error at the cam by a new symbol h.

The plotting mechanism is designed to transform cam r into plotted ordinates, $F(\text{cam } r)$ inches, on alternative ordinate scales whose functional form $F(r)$ is selectable by using interchangeable cams. Actually, however, the transformation includes a small additive ordinate displacement, ϵ inches, which may accumulate in—(1) adjusting the counter to agree with the reference marks on the cams when set to the follower, (2) nonreproducible clamping of the cam assembly to its shaft, (3) adjusting the coupling to the pen lead-screw, (4) positioning the plot-sheet on its drum, and (5) trimming the top edge of the sheet by which it is positioned. Also, the actual transformation involves the fractional excess length ζ of the printed ordinate scale, which ranges up to ± 0.005 due to the action on the plotting paper of humidity changes since printing. Consequently

$$\text{plotted } F(r)=(1-\zeta)[F(\text{cam } r)+\epsilon]+\zeta f, \quad (5)$$

where f is the value of $F(r)$ at the top edge of the plot-sheet.

Expanding Eq. (4) into a Taylor's series and introducing it into Eq. (5) gives the absolute difference Δ between the plotted $F(r)$ and true $F(r)$ as

$$\Delta F(r)=\epsilon+\zeta[f-F(r)]+hF'(r). \quad (6)$$

The magnitude of the neglected remainder in the series expansion reaches half that of the retained stray effects at the limits of h where

$$hF''(r+\theta h)=\pm F'(r),$$

$0<\theta$ undetermined <1.

Equation (6) gives the total uncompensated photometric error.[20]

V. Compensation of Photometric Errors

100-percent plot

In inches, $F(r)=10r$, $F'(r)=10$ and $f=10.5$. If the least readable ordinate increment be taken as $0.01=\partial F(r)=F'(r)\cdot\partial r=10\cdot\partial r$, then it corresponds to $\partial r=0.001$ absolute error. Reading r to 1 percent (relative) is possible only when $r>0.1$, therefore. Since $r<0.2$ will usually be measured on another plot, the present problem is to minimize on the 100-percent plot all absolute errors in the range $0.1<r<1$. It should be noted that this will minimize errors with regard for their "readableness" rather than for their practical importance, and that a uniform ordinate scale does not have the advantage of special scales exemplified below which display tolerances in a uniformly readable way.

From Eq. (6)

$$\begin{aligned}\Delta r=\Delta F(r)/10 &= -2\beta r^{\frac{1}{2}}(1+r)+0.1\epsilon\\ &\quad +\zeta(1.05-r)-2i\gamma r^{\frac{1}{2}}(1+r)\\ &\quad +\eta(1-r^2)-j\mu(1-r)^2-\nu r \quad (7)\end{aligned}$$

without restriction on the size of the sum of stray effects previously denoted by h, since $F''(r)=0$.

This error can be demonstrated if one makes $\epsilon=0$ by adjusting the pen and the counter to agree with the reference marks ($r=0.5$, 0.2, 0.15,

[20] Wave-length errors have been treated by Gibson, reference 11, p. 378.

0.1) on the cam, and makes $\beta=0$ by extinction of the reference beam at counter reading 9991 (see footnote 19). Then

$$\Delta r=\zeta(0.3-r)+\eta(1-r^2)-j\mu(1-r)^2-(\nu+4i\gamma)r, \text{ approx.}$$

For the unreduced strays which reach $\gamma=0.001$, $\zeta=\pm0.005$, $\eta=-0.017$, $\mu=0.01$ and $\nu=\pm0.01$, the absolute error at high values of r can reach -0.015, and at low values can reach -0.03; these are, respectively, about 15 and 30 times larger than the least readable error. Such large errors will not ordinarily be observed because the adjustment of β and ϵ is usually not made strictly according to the above procedure, but is made empirically to give less error by purposely introducing a compensating error. For instance, if β is adjusted instead to give no error for a unit transmission standard, as directed by the instruction folder, then $\beta=-\nu/4$ and

$$\Delta r=\zeta(1-r)+\eta(1-r^2)-j\mu(1-r)^2-4i\gamma r.$$

It is even more important to adjust ϵ to compensate the larger errors at low values of r.

Consequently β and ϵ should each be set at the value which is required to minimize ∂r. Determining these required values is facilitated if the other components of ∂r be plotted as ordinates against an abscissa scale of r having uniform divisions of $2r^{\frac{1}{2}}(1+r)$ which is the coefficient of $-\beta$ in Eq. (7). By way of illustration, the coefficients of ζ and $-i\gamma$ are so plotted in Fig. 3 as full lines marked off in values of r. First of all, $i\gamma$ causes a nonreproducible error which cannot be compensated by another reproducible one. The coefficient of $-i\gamma$ is the same as the coefficient of $-\beta$, and so is given by the ordinates under a straight line, as shown. If γ reaches 0.001 and $\partial r=0.001$, the ordinate limit within which $i\gamma$ causes nonreadable errors is 1, as also shown. In the succeeding figures, this same information will be given more simply by designating the abscissae as coefficients of $-i\gamma$ and appending the coefficient limit for nonreadable errors. All the other strays cause reproducible errors which can be largely compensated. Secondly, the combined contribution to Δr of the terms in β and ϵ is represented on this plot by a straight line whose slope and height are, respectively, determined by β and ϵ. This contribution can thus be readily chosen to compensate the contributions of the other reproducible components. For instance, if the photometer readings be made to have no error at $r=0$ and $r=1$ by adjustment of β and ϵ with standard samples, then the absolute error contributed by ζ must also at these points be zero and at intermediate points be given by ζ times the coefficient represented by the ordinate difference between the full-line curve and the dashed straight line in the figure. The absolute error contributed by ζ is thus reduced twelve times, at least, by compensation which refers to these particular standard samples. It is to be noted that in this procedure the choice of two standards, for which the photometer is adjusted to give no error, compensates each stray effect independently of the others and independently of its own magnitude, without ever calculating the values of β and ϵ by which it is accomplished.

As a matter of fact, another choice of standards is preferable in the present example for two reasons. In the first place, although only the zero and unit transmission standards are known without experimental error, the zero standard must not be used for compensation of errors because it balances on the modified profile of the cam. If it be so used in conjunction with the unit standard,

$$\Delta r=-0.2(\eta-j\mu)^{\frac{1}{2}}(1-r)+\eta(1-r^2)-j\mu(1-r)^2,$$

which reaches 5 times the least readable error even for the reduced strays ($\eta-j\mu=+0.001$) allowing the instrument to balance. In the second place, if the straight line were drawn through the curve at $r=0.35$ and $r=0.90$ the ordinate differences would be another nine times reduced in the range $0.1<r<1$. To indicate the degree to which ordinate differences ought to be reduced, it is helpful to lay off on the plot the limit within which they produce nonreadable errors. If ζ reaches ±0.005 as stated, its coefficient to produce $\partial r=0.001$ is ±0.2 as shown. In this case, any two (reasonably different) standards for which $r>0.01$ will give adequate compensation, and so they may be chosen with regard to minimizing some other stray effect.

Obviously, straight lines on the plot remain straight lines in any linear transformation which involves adding to the ordinates any constant or any multiple of the abscissae. By this means, the illustrative curve of Fig. 3 is better displayed

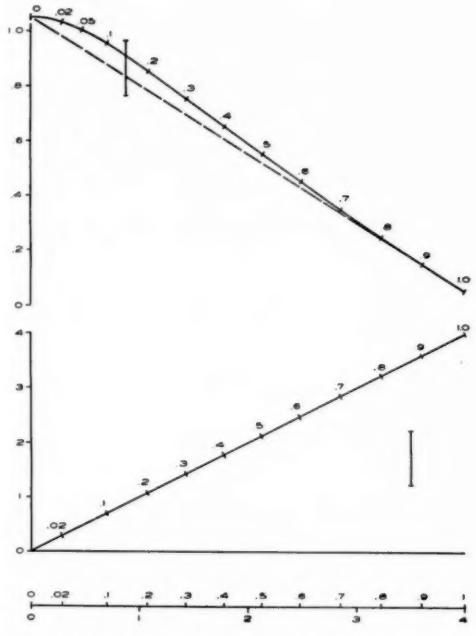


FIG. 3. Compensation of errors—illustrative example wherein, for all values of r as abscissae, the compensated error due to ζ is given by ζ times the coefficient difference between the curve and the straight line which crosses the curve at the values of r chosen for the standards used in adjustment. The coefficient difference is indicated which gives a barely readable error for an appropriate value of ζ stated in the text. The nonreproducible error due to γ is given by $-i\gamma$ times the coefficients (ordinates or abscissae) so marked, and the coefficient limit for similar nonreadable errors is indicated. Legend for upper ordinate scale—coefficient of ζ; legend for lower ordinate scale—coefficient of $-i\gamma$; legend for top abscissa scale—relative transmission or reflectance r; legend for bottom abscissa scale—coefficient of $-\beta$.

in Fig. 4 which shows the stray effects in Eq. (7) when transformed to

$$\Delta r=(\zeta+\nu)[0.5r^{\frac{1}{2}}(1+r)-r]+\eta[0.5r^{\frac{1}{2}}(1+r)-r^2]$$
$$-k\mu[0.5r^{\frac{1}{2}}(1+r)-2r+r^2]-(j-k)\mu(1-r)^2$$
$$+[-4\beta-4i\gamma-\zeta-\eta+j\mu-\nu][0.5r^{\frac{1}{2}}(1+r)]$$
$$+(0.1\epsilon+1.05\zeta+\eta-j\mu),$$

where $k=0$ when transmission standards are used in compensation, and $k=1$ when reflection standards are used. The indicated limits pertain to the same unreduced strays as just mentioned. In the optimum case when 0.25 and 0.85 standards are used, absolute errors in the range $0.1<r<1$ due to ζ and ν are entirely negligible, those due to η and $k\mu$ are cumulative with each at worst barely readable, and the one due to γ increases proportionally with r to a value $4\,\partial r$ ("four times the minimum readable"). A large error reaching $10\,\partial r$ occurs if transmission standards are used for reflection measurements and vice versa. The adjustments should be made at a middle wave-length because even then the uncompensated wave-length variation of κ, included in η, will itself give errors of $3\,\partial r$ in the lower corners of the plot.

By reducing the stray light, the η and μ errors can be reduced around twenty times with several advantages: 0.15 and unit standards can be used, the plot shows no reproducible errors down to $r=0.01$, and transmission standards can be used for reflection measurements.

20-percent plot

Here $F(r)=50r$, $F'(r)=50$ and $f=10.5$. Again, if the least readable ordinate increment be taken as $0.01=\partial F(r)=F'(r)\cdot\partial r=50\cdot\partial r$, then it corresponds to $\partial r=0.0002$ absolute error. Reading r to 1 percent is possible when $r>0.02$. Samples for which $r<0.04$ are better read on the log plot, see below. Nevertheless, minimize absolute errors throughout the entire range of the true cam profile, $0.004<r<0.2$.

From Eq. (6)

$$\Delta r=(\zeta+\nu)[0.5r^{\frac{1}{2}}(1+r)-r]-\eta r^2$$
$$-k\mu[0.5r^{\frac{1}{2}}(1+r)-2r+r^2]-(j-k)\mu(1-r)^2$$
$$+[-4\beta-4i\gamma-\zeta+k\mu-\nu][0.5r^{\frac{1}{2}}(1+r)]$$
$$+(0.02\epsilon+0.21\zeta+\eta-k\mu)$$

without restriction on the size of h. In corresponding Fig. 5, the indicated limits pertain to the same unreduced strays as in Fig. 4. In the optimum case when 0.013 and 0.15 standards are used, absolute errors due to ζ and ν are barely readable, those due to η and $k\mu$ are mutually compensating and each is barely readable, and the one due to γ increases proportionally with r to a value of $5\,\partial r$. A very large error averaging $40\,\partial r$ (or between 12 percent and 20 percent of $r=0.05$) occurs if transmission standards are used for reflection measurements and vice versa. The adjustments should be made at a middle wave-length because even then the uncompensated wave-length variation of κ, included in η, will itself give errors of $17\,\partial r$ (equals 7 percent of $r=0.05$) at the sides of the plot. Furthermore, since cam $r=r+\eta-j\mu$ at low values, and since

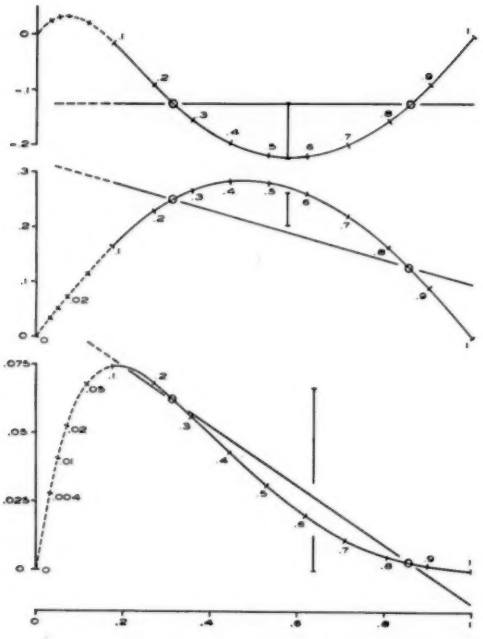


FIG. 4. Compensation of errors on the 100-percent plot. Legend for top ordinate scale—coefficient of $-k\mu$; legend for middle ordinate scale—coefficient of η; legend for bottom ordinate scale—coefficient of $\zeta+\nu$; legend for abscissa scale—coefficient of $-4i\gamma$, tolerance 0.25.

it must not be used below 0.003 due to the modified cam profile, r can be measured only down to 0.02 transmission or 0.03 reflectance.

By reducing the stray light, the η and μ errors can be reduced around twenty times, whereupon the uncompensated error at extreme wavelengths becomes negligible and r can be measured down to 0.004 without reproducible error. If μ can be reduced fifty times or more (as in the prototype instrument, see p. 281 above) then transmission standards can be used for reflection measurements.

It is important to adjust the 100-percent and 20-percent plots entirely independently. Large errors, as given by the fragmentary straight lines in Fig. 5, result from any attempt to simplify the procedure by making only a simultaneous 100-percent adjustment on the 100-percent plot and 0.013 adjustment on the 20-percent plot. In this case, any relative displacement between the cams on their shaft would lead to a superposed error which might increase or reduce the net error.

Log plot

For the log, or optical density, cam which has been supplied[21] with the instrument, $F(r) = -1.45 \ln r^{-1}$, $F'(r)=1.45/r$ and $f=0.5$. The least readable ordinate increment of $0.01=\partial F(r) = F'(r)\cdot\partial r=1.45\partial r/r$ corresponds to $\partial r/r=0.7$ percent relative error. Thus visual tolerances are uniformly readable throughout the whole range $0.001<r<1$.

From Eq. (6)

$$\Delta r/r=\zeta \ln r^{-1}-(\eta-k\mu)[30r^{-1}(1+r)-r^{-1}+1] -(j-k)\mu(1-r)^2/r +[-4\beta-4i\gamma+60(\eta-k\mu)][0.5r^{-1}(1+r)] +(0.69\epsilon+0.345\zeta-\nu)$$

when $r>0.001$ and $-0.0004<\eta-j\mu<+0.001$ as follows from $F''(r)=-1.45/r^2$. This analysis will therefore hold only for the reduced strays: $\gamma=0.001$, $\zeta=\pm0.005$, $\eta=0.001$, $\mu=0.0005$ and $\nu=\pm0.01$. Figure 6 shows by the reversed abscissa scale that here β must be adjusted at the low standard and ϵ at the high standard. In the optimum case when 0.0014 and 0.25 stand-

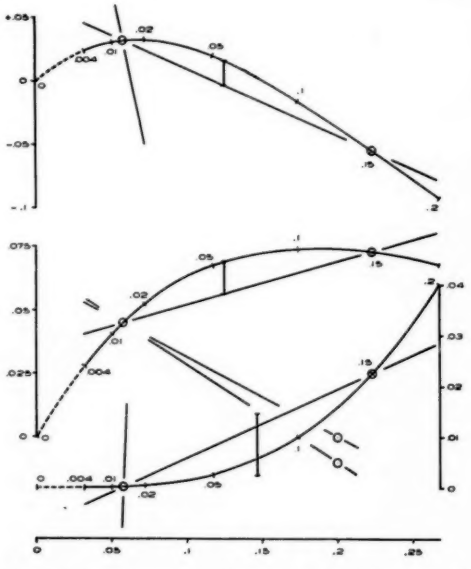


FIG. 5. Compensation of errors on the 20-percent plot. Legend for top left ordinate scale—coefficient of $-k\mu$; legend for bottom left ordinate scale—coefficient of $\zeta+\nu$; legend for bottom right ordinate scale—coefficient of $-\eta$; legend for abscissa scale—coefficient of $-4i\gamma$, tolerance 0.05.

[21] Gibson, reference 11, p. 374.

ards are used, the relative error due to ζ is negligible, that due to η is sometimes partially compensated by that due to $k\mu$ but alone it reaches $15\,\partial r/r$, and the one due to γ reaches $9\,\partial r/r$. A very large error reaching $70\,\partial r/r$ occurs if transmission standards are used for reflection measurements and vice versa. With unreduced stray light, these errors are many times larger, of course.

Consideration of the large magnitude of the unavoidable error due to η points out that the plot should be used only above $r=0.01$ or, better, that an improved log plot should be employed to cover only this range. For the latter case, $F(r)=2.17 \ln r$, and the least readable curve displacement corresponds to $\partial r/r=0.5$ percent relative error. Changing the "30" in Eq. (6) to "25" leads to the corresponding Fig. 7. If the 20-percent-plot standards are used for economy, the reproducible error reaches only $2\,\partial r/r$ and the nonreproducible error only $5\,\partial r/r$. An error of $10\,\partial r/r$ occurs if transmission standards are used for reflection measurements and vice versa.

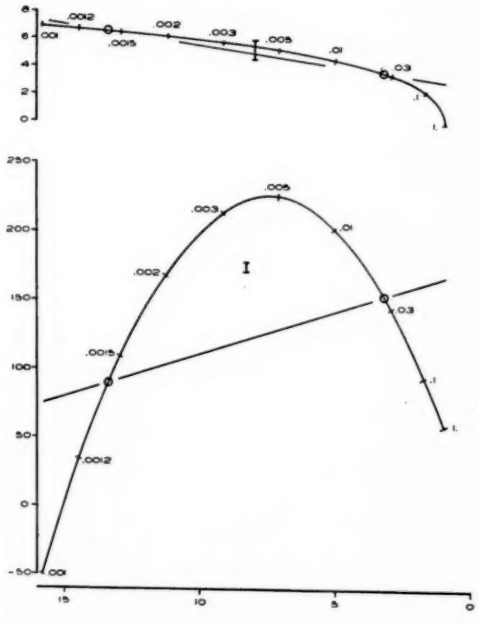


FIG. 6. Compensation of errors on the G.E. log plot. Legend for top ordinate scale—coefficient of ζ; legend for bottom ordinate scale—coefficient of $\eta-k\mu$; legend for abscissa scale—coefficient of $-4i\gamma$, tolerance 1.75.

Loglog plot

For the loglog, or solution strength, cam which has been supplied[22] with the instrument, $F(r)=-1.53 \ln \ln r^{-1}$, $F'(r)=1.53/r \ln r^{-1}$ and $f=7.5$. The least readable ordinate increment of $0.01=\partial F(r)=F'(r)\cdot\partial r=1.53\cdot\partial r/r \ln r^{-1}$ corresponds to a strength error $-\partial c/c=\partial r/r \ln r^{-1}=0.7$ percent which is uniformly readable throughout the whole transmission range $0.001<r<0.99$. An ordinate increment which is uniform at all values of r implies a parallel vertical displacement of curves due to strength changes; this greatly simplifies interpretation of the curves.[23]

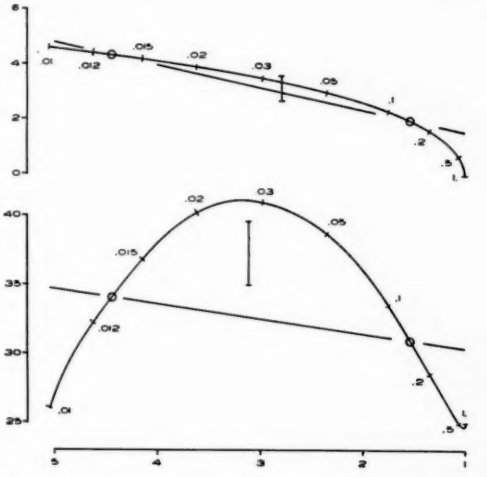


FIG. 7. Compensation of errors on an improved log plot. Legend for top ordinate scale—coefficient of ζ; legend for bottom ordinate scale—coefficient of $\eta-k\mu$; legend for abscissa scale—coefficient of $-4i\gamma$, tolerance 1.

From Eq. (6)

$$\begin{aligned}-\Delta c/c=&\zeta \ln \ln r^{-1}+\eta(1-r^2)/r \ln r^{-1}\\&+\nu[0.5r^{-\frac{1}{2}}(1+r)-1]/\ln r^{-1}\\&-j\mu(1-r^2)/r \ln r^{-1}\\&+[-4\beta-4i\gamma-\nu][0.5r^{-\frac{1}{2}}(1+r)/\ln r^{-1}]\\&+(0.653\epsilon+0.49\zeta)\end{aligned}$$

if $r>0.001$ and $-0.0004<\eta-j\mu<-0.0012$. This analysis, like that for the log plot, will hold only for the same reduced strays. Figure 8 does not show a reversed abscissa scale as in Fig. 6, but

[22] Gibson, reference 11, p. 375.
[23] U. S. Patent No. 2,176,013.

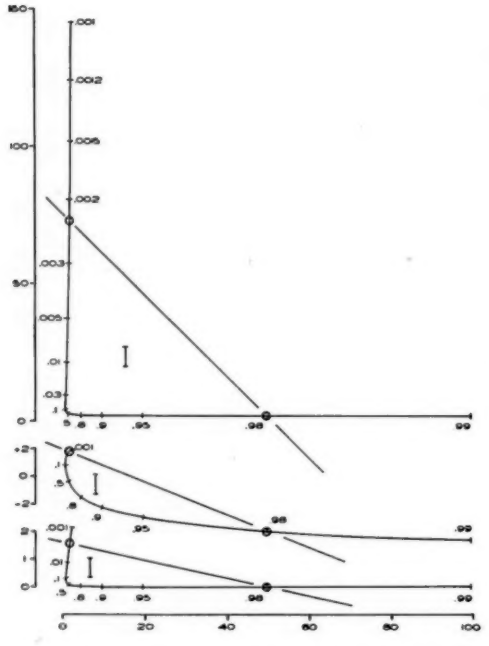


FIG. 8. Compensation of errors on the G.E. loglog plot. Legend for top ordinate scale—coefficient of η; legend for middle ordinate scale—coefficient of ζ; legend for bottom ordinate scale—coefficient of ν; legend for abscissa scale—coefficient of $-4i\gamma$, tolerance 1.75.

it does show similarly large errors reaching $10\,\partial\mathbf{c}/\mathbf{c}$ due to η, and $60\,\partial\mathbf{c}/\mathbf{c}$ due to γ.

An improved loglog cam covering only the range $0.01<r<0.95$ will show strength differences of 0.5 percent. According to Fig. 9, the reproducible errors are then barely readable when 0.025 and 0.90 standards are used, while the error due to γ reaches $20\,\partial\mathbf{c}/\mathbf{c}$. The prototype instrument was equipped with a loglog cam of this preferred sort, and moreover avoided the large nonreproducible error due to γ by using for the cam follower simply a hardened pin fixed to a freely moving follower arm.

VI. CONCLUSION

Because of the relatively large amount of stray light in the instrument as sold, it is particularly important to adjust the plotting with each cam by reference to two known samples. Even then, the compensation of photometric errors is good in only a restricted wave-length range because the proportion of stray light varies with wavelength; thus an error reaching nearly twenty times the least readable occurs with dark samples—for which a barely readable error has considerable practical importance.

This error is eliminated if the instrument be slightly altered to reduce the amount of stray light. Also, very dark samples can then be measured without instability, and so the microswitch can be removed. Furthermore, appropriate log and loglog cams can then be used respectively to make visual and solution-strength tolerances uniformly and easily readable, but these cams should be somewhat different from the ones supplied with the instrument. Finally, adjustment of the plotting mechanism with standards near $r=0.013$ and 0.15 will then suffice to make the 100-percent, 20-percent and log plots without important reproducible photometric errors except such as may be caused by uncertainty in the standards, while for the loglog plot 0.025 and 0.90 standards correspond.

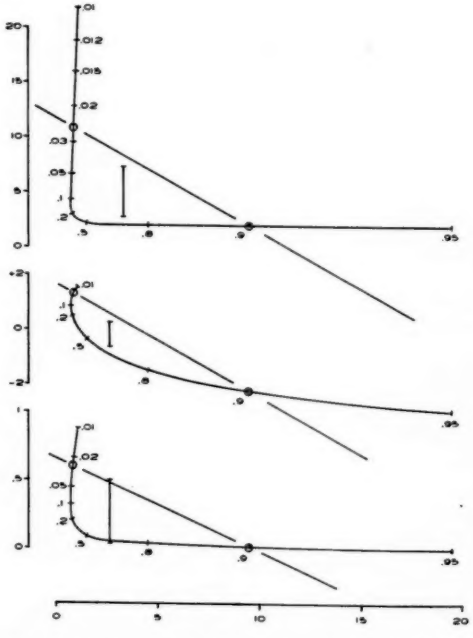


FIG. 9. Compensation of errors on an improved loglog plot. Legend for top ordinate scale—coefficient of η; legend for middle ordinate scale—coefficient of ζ; legend for bottom ordinate scale—coefficient of ν; legend for abscissa scale—coefficient of $-4i\gamma$, tolerance 1.

In spite of wear, the radius of the roller on the cam follower must be maintained uniform within half a thousandth of an inch to prevent on the 100-percent, 20-percent and log plots a non-reproducible photometric error which cannot be compensated but which, however, can be eliminated by replacing the roller with a fixed pin. It follows that the profiles of these cams must be equally accurate,[24] while for the loglog cam and roller one ten-thousandth inch corresponds.

Specifically, to make photometric errors less than readable on the 100-percent and 20-percent plots, (1) mask out the stray slit-outline images at stop **14**, Fig. 1. (2) Remove the stray light **12** reflected from tube **10**. (3) Keep optics clean and the beam clear of obstruction. (4) Remove the microswitch, since the photometer should now balance with a zero sample. (5) Keep the cam follower-roller round and concentric to 0.0005 inch; this will require frequent replacement and considerable care against damage in changing cams. (6) When using the 100-percent cam, adjust the photometer prism azimuth to give a correct 100-percent line and adjust the pen screw coupling to give a correct reading for a transmission standard near 0.15. (7) When using the 20-percent cam, adjust the photometer prism azimuth to give a correct reading for an 0.15 standard, and adjust the pen screw coupling to give a correct reading for a standard near 0.013; use transmission standards for transmission measurements, and reflection standards for reflection measurements.

[24] Michaelson, reference 10, p. 368.

An Improved High Speed Recording Spectrophotometer

GEORGE R. HARRISON AND EDWARD P. BENTLEY
George Eastman Research Laboratories of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received March 15, 1940)

An automatic recording spectrophotometer designed to cover the range 10,000 to 2000A is described. With present light sources the instrument will trace absorption curves at high speed from 9800A to 3400A, and can be used somewhat more slowly to cover the spectrum to 2300A. A ten-foot concave grating monochromator with fixed slits is used to provide a spectral band 0.5 to 10A wide, the purity available depending on the light intensity and the speed of recording desired. An 11-stage electron multiplier is used to balance a light beam which has passed through the sample to be measured, against the same beam later reduced by a photometric disk by a recorded amount. An electric "memory" device is used to accomplish this balance, and at the instant of balance a spark is passed through a piece of suitable graph paper wrapped around a rotating cylinder. Twenty absorption measurements can thus be made and recorded per second. The instrument will plot either transmission or density values against wave-lengths on a linear scale, to an accuracy of about 1 percent.

IN a previous paper was described a new type of recording spectrophotometer designed to trace automatically and at high speed the transmission curves of filters or solutions in the range 10,000 to 2000A.[1] This device, simplified and improved, is now in routine operation; with it density or transmission curves in the range 9800A to 3400A can be traced in 70 seconds, and the additional range 3400 to 2300A can be covered in a few minutes. The limitations in range, which are being overcome, arise almost entirely from limitations in the light sources available.

To simplify the recording process and eliminate the necessity of developing photographic records, the desired curve relating density (or transmission factor) to wave-length is now traced by a spark discharge through a 11×17-inch sheet of special graph paper wrapped around a rotating drum. As many as twenty transmission measurements can be made and thus recorded per second, a feature particularly useful for the study of unstable solutions, and for measuring chemical reaction rates.

The basic advantages of the instrument arise from: (1) coverage of broad spectral range, with high light-intensity and purity, through the use of a concave-grating monochromator; (2) use of an electron-multiplier tube with quartz window to measure light intensities; (3) obtaining of high speed by use of an all-electric "balancing" system for matching light intensities; (4) use of a condenser "memory device" to balance a monochromatic beam of light, reduced by passing through the sample, against itself when later reduced by a recorded amount; (5) use of a mechanically-driven oscillating biprism for switching the measuring beam from sample to standard. Most of these devices could be used to advantage separately in simpler photometric systems. The instrument which results from their combination will be described here in a form especially designed for transmission and density measurements; it could equally well be adapted to other problems of homochromatic photometry, such as the determination of the spectral energy distribution of radiation from a lamp in terms of that from a standard lamp.

A diagram of the working parts of the simple monochromator used is shown in Fig. 1, which also depicts the photometric system. A six-inch concave grating G of ten-foot radius, ruled with 15,000 lines per inch in aluminum on glass by R. W. Wood at Johns Hopkins University, is mounted on a carriage with ten-inch travel so that it can be rotated and translated by means of cams A and B. The grating was ruled to throw most of its light in the first order, and is found to be fully as bright as a prism system of equal size, and more free from scattered light. Gratings of 35 ft. and of 3 ft. radius have been used in the instrument with satisfactory results, but the 10-

[1] G. R. Harrison, *Proceedings of the Sixth Conference on Spectroscopy* (Wiley, 1939), p. 91. (See also G. R. Harrison, J. Opt. Soc. Am. **28**, 49 (1938).)

ft. radius gives a convenient compromise between the disadvantages of extreme length and those of high aperture ratio.[2]

Both entrance slit X and exit slit Y are fixed in position, and can be adjusted to any width from 0 to 2 mm. Since the dispersion is 5.5A/mm, purity greater than that obtained with most prism monochromators can be realized even with very wide slits, and when extreme resolution is required the slits can be narrowed. The approximately uniform dispersion of the grating makes variation of slit-width unnecessary in passing through the spectrum. To realize full spectral purity, the exit and entrance slits should be together; actually, however, it is found that no loss of purity appreciable for the present purpose results when they are separated by the 18 cm needed to permit convenient disposition of the photometer system. The slight astigmatism introduced at long wave-lengths does not affect the operation of the instrument, which is very efficient in transmitting monochromatic radiation between 12,000 and 2000A. To eliminate higher orders a Noviol glass filter is snapped by an electromagnet into the beam at 3600A when the spectrum is traversed toward longer wave-lengths, and out at 3500A for traverse in the opposite direction, while a yellow filter operates at 6100A and 6000A, respectively, for the two traverses. Thus a measurement lost during the motion of the filter can be obtained with a traverse in the opposite direction.

Light from the lamp L is focused in a vertical line on slit X by a 2-inch crystal-quartz cylindrical lens C, and in a horizontal band on the face of grating G by a similar lens D of longer focus. Thus the entrance slit X is uniformly illuminated along its length, so that the photometric sector N can be caused to reduce the intensity of the transmitted light by known amounts by varying the length of the slit. The focal lengths of C and D were so chosen that when the lamp L, its housing, and lens C are moved by a cam in such manner that the light of the wave-length being used at the moment is sharply focused horizontally on slit X, it will also be focused vertically on the grating. Thus the chromatic aberration of the lenses is compensated, and focal isolation is used to reduce the intensity of scattered light.

After leaving the exit slit Y the monochromatic beam passes through the crystal-quartz biprism P of 168° angle, which deflects the beam so that this passes through either the measuring cell E or the comparison cell F, depending on its position. The biprism oscillates sinusoidally once per measuring cycle, and has been offset so that the beam is in one position during 90° of the cycle and the other during 270°, while the shift occurs during the time the light is cut off. The prism can be oscillated 30 times per second without difficulty.

The two-inch cylindrical quartz lens Q focuses the face of the grating vertically on the sensitive surface of the electron multiplier M, while the cylindrical quartz lens H makes the light parallel horizontally, and the similar lens I focuses the slit Y horizontally on the surface of the multiplier, to insure that the beam will always strike the same area. The area covered by the uniform monochromatic beam at the measuring position E is about 10×18 mm. The dispersion of light produced in biprism P is compensated by the dispersion in lens H, which, with I, is moved by a cam to keep the light between H and I parallel in the horizontal plane at all wave-lengths. In the vertical plane the beam deviates by a negligible amount from parallelism.

Careful testing of this system shows that it gives a light beam of high spectral purity, and that varying the length of slit X gives a proportional and neutral variation in intensity of the light passing through either position E or F. The extra device introduced in the original

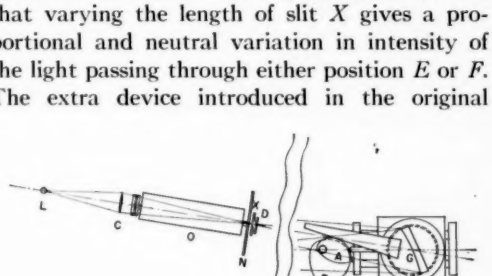


FIG. 1. Layout of principal parts of the grating monochromator. The tracks of the grating-carriage at G are inclined toward a point midway between the entrance slit X and the exit slit Y. The drawing is not to scale.

[2] G. R. Harrison, *Proceedings of the Fifth Conference on Spectroscopy* (Wiley, 1938), p. 31.

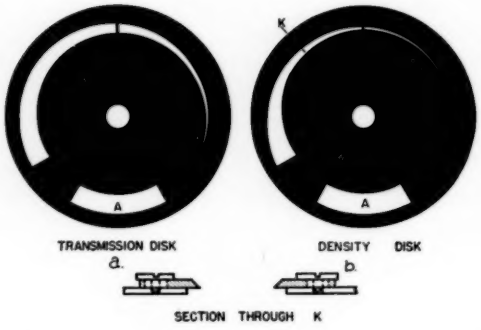


FIG. 2. The two photometric disks in which the length of the entrance slit is varied with angle linearly (a) and logarithmically (b). The section through K shows the movable edges of the openings, which can be adjusted to give accuracy to 1 percent.

design to insure neutrality[1] was found to be unnecessary, so long as the lenses and biprism used are clean and free from flaws. The photometric system does not depend for its accuracy on the adjustment or shape of the light source; however, to obtain the greatest light flux, the source should be long enough to fill the ruled portion of the grating at all wave-lengths, and must be broad enough to fill the slit X at its widest. A 100-watt clear-bulb coiled-coil filament lamp is found satisfactory for the range 9800 to 3400A.

The biprism must be kept free from dust, grease and scratches, and must transmit uniformly along its length; these requirements are more easily fulfilled with a prism than with the less permanent oscillating mirror originally planned for switching the light beam.

The recording graph paper is wrapped around the cylinder O, 17 inches long and about 4 inches in diameter. The shaft on which this cylinder is mounted carries also one of the photometric disks (Fig. 2) and the commutators described below, and actuates the cam which oscillates the biprism. Two types of graph paper are provided; type A, for use with the linear disk (Fig. 2a) has abscissas marked from 2000 to 10,000A in 20A intervals which can be read to 2A, and ordinates giving percentage transmission from 0 to 100 percent; type B, for use with the logarithmic disk (Fig. 2b), has wave-length calibrations similar to those of A, but has ordinates reading densities from 0.0 to 2.0 in twenty steps. Both types of paper are blackened on the back to increase visibility of the holes punched by the recording spark; when type A is used it is wrapped around drum O face outward, while with type B the blackened side is placed outwards. Thus is avoided the necessity of reversing the direction of rotation of the drum when changing from transmission to density measurements.

The accuracy of the instrument is limited by that of the openings in the photometric disks. In Fig. 2 is shown a device used for adjusting the disk openings, for assistance with which we are indebted to instrument-maker Carl G. Selig. After the opening in the disk has been cut slightly larger than needed, two beveled curved strips are screwed to its edges. These, slotted every few millimeters, can be set very accurately under a microscope. The length of the slit X can thus be controlled to within 1 percent over the range 25 mm to 0.25 mm.

Various electron multipliers, obtained from Radio Corporation of America, Farnsworth Television Corporation, and Western Electric Company, have been tried. All of those found satisfactory were of the 10- or 11-stage electrostatic-focusing type, especially selected for low dark current. We have obtained a multiplier with quartz window by providing the envelope for this, into which the multiplier was built through

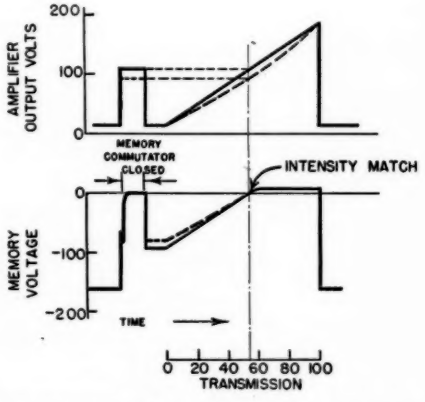


FIG. 3. Response of the amplifier and the memory condenser during a photometric cycle. During the first part of the cycle, when the memory commutator is closed, the light is passed through the sample being measured; thereafter it passes through the blank cell and is reduced by the photometric disk until an intensity match is produced. The dotted curves show how the null method used avoids dependence on a linear response of the circuit.

the kind cooperation of the Farnsworth laboratories. Two multipliers with dark currents as great as 10^{-5} equivalent lumen were found to improve greatly with use; others with initial dark currents as low as 10^{-7} equivalent lumen developed large dark currents after a few weeks. Selected 11-stage commercial electron multipliers were found to give ample sensitivity for our purpose, and adequate stability when provided with a properly controlled power-pack. Variations in multiplier plate voltage produce output current variations proportional to the variation of voltage raised to the power of the number of stages, so if output steady to 0.3 percent is desired from a 10-plate multiplier it is necessary to control plate voltage to 0.03 percent. Careful design of a stabilized power-pack makes this degree of steadiness possible.[3]

The photometric cycle is illustrated in Fig. 3. When slit X (Fig. 1) is traversed by section A of the photometer disk (Fig. 2) light is passed through the filter or solution being measured at E, and a "memory condenser" is charged by the multiplier output to a potential which is a measure of the intensity of the light transmitted. The beam of light is then cut off by further rotation of the disk and the biprism P moves so that on reappearance the beam traverses the blank cell F. As disk N continues to turn the light intensity is increased until the voltage applied to the condenser equals that of the charge stored in it, at the point marked "intensity match" in Fig. 3, when a spark passes through the graph paper which has been wrapped around the drum O in such position that its calibration marks coincide with those on the photometer disk. The disk continues turning forward to position A, and the measurement cycle is repeated, either at the same wave-length, or at a new wave-length if the grating cam has been turned. The measurement cycle can be performed as quickly as desired provided the "electrical resolving power" of the system is sufficiently high with the light available. In practice 0.05 second or more per measurement is used, but the limit thus far has been set by mechanical considerations resulting from imperfect balance of the cylinder.

It will be seen from Fig. 3 that the electrical system need not be linear in response, since a null method is used. A block diagram of the system is shown in Fig. 4, while details of the circuit are given in Fig. 5. The output current of the electron multiplier is fed through a logarithmic amplifier[4] to a 2-stage d.c. amplifier, which feeds the "memory unit" consisting of a 0.01-mf mica condenser and appropriate commutators mounted on the shaft of O. With these commutators the condenser is charged during the first part of the cycle, then insulated until "electrical balance" is produced. When the voltage applied to the condenser equals its internal voltage the 884 tube is fired and a spark is released through the graph paper.

Separate variable-speed motors operate the measurement-cycle drive and the wave-length drive, which turns and moves the grating and moves the spark electrode along the graph paper linearly with wave-length at a maximum rate of 100A/sec. Measurements can be made at wave-

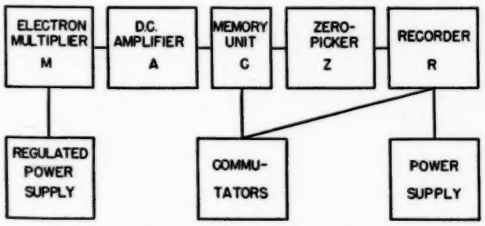


FIG. 4. Block diagram of the electrical circuit.

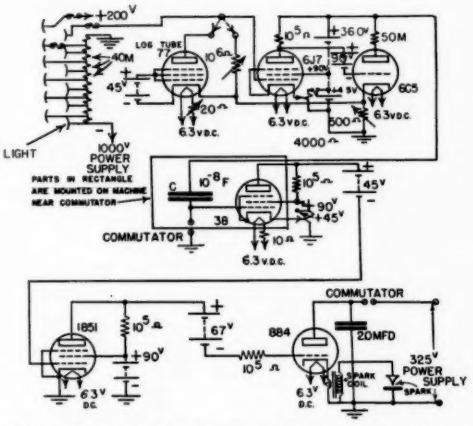


FIG. 5. Details of the electrical circuit, from the electron multipler which measures the light to the sparking device which records the balance point.

[3] V. K. Zworykin, J. Opt. Soc. Am. **29**, 84 (1939).

[4] R. E. Meagher and E. P. Bentley, Rev. Sci. Inst. **10**, 336 (1939).

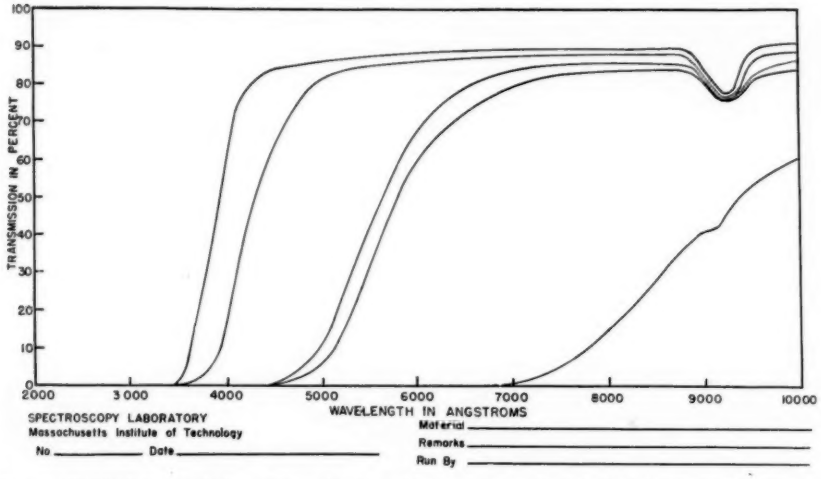


FIG. 6. Typical transmission curves for transformer oils obtained with the recording spectrophotometer in 80 seconds each.

length intervals as closely spaced as desired. The spark jumps from a platinum wire held in a quartz capillary to a thin copper foil permanently wrapped around the drum under the paper, producing in the paper a fine hole whose position can be controlled to within a fraction of a millimeter. A transmission or density curve can readily be traced through these holes when the chart is placed on a viewing box; Fig. 6 shows some typical transmission curves.

In those parts of the spectrum in which ample light is available, the average deviation of individual points from a smooth curve seldom exceeds 1 percent, and curves taken in the visible region check within 1 percent curves for the same samples made with the Hardy color-analyzer.[5]

When a plotted curve is not required, density or transmission values can be recorded photographically at desired wave-length intervals. The circuit can be arranged to fire a stroboscope lamp instead of the spark, and the flash from this lamp can be used to photograph on motion picture film, at the instant of balance, the scale on the edge of the photometer disk, together with a dial driven from the spark drive-screw, which reads wave-lengths directly.

Though measurements made with the instrument are found to be almost independent of light intensity over a broad range, for the highest precision it is desirable to operate at the optimum intensity at all wave-lengths. Also variations in light intensity should not exceed 1 percent during the time of one measurement cycle as the spectrum is traversed. A continuous source is thus desirable, though not necessary if a pause is made during each measurement. Hand monitoring of the light source is now used, the voltage on a 110-volt lamp being changed from 60 volts at 7000A to about 180 volts at 9800 and 3400A, but arrangements are being made for automatic monitoring with a cam-operated potentiometer, and for an automatic output-control device for the multiplier system.

For the range 3400 to 2200A we now use a high pressure quartz mercury arc as light source. The measuring cycle is repeated continuously, but the wave-length traverse is operated by hand, the spark being turned on only when a line is set on. A high intensity hydrogen lamp has been constructed in the hope that a combination lamp could be made to cover the entire desired spectral range, but thus far this lamp has lacked satisfactory life in the form used. Several other possibilities are now under investigation, and it appears probable that when the light problem is solved the entire spectral range 10,000 to 2000A can be covered in 100 seconds.

The development of this automatic broad-range spectrophotometer has been supported in part by the Cabot Fund for Solar Energy Research, and in part by the Rockefeller Foundation, for which assistance we are deeply grateful.

[5] A. C. Hardy, J. Opt. Soc. Am. **25**, 305 (1935).

Production Color Analysis of Kinescope Screens

T. B. PERKINS
RCA Manufacturing Company, Inc., Harrison, New Jersey
(Received March 21, 1940)

An apparatus for analyzing the "degree of whiteness" of kinescope screens in production is described. A three-color process of producing a matching color for any acceptable kinescope is discussed and design given.

WITH the advent of white kinescope screens, it became necessary to have some method of testing "degree of whiteness." This may be accomplished by several methods. The most scientific analysis, of course, is made by spectrographic means, but this method is far too complicated and time-consuming for production testing. More practical methods consist of comparison tests, where either each color component is measured separately by photometric or photoelectric means, or a series of matching colors, within whose limits the final screen must catalog, are set up as standards.

The method which will have the most value must be one which gives complete and reproducible data for each tube; it must be sensitive enough to identify color differences, which would be objectionable to observers, in kinescope screens placed side by side, and must be stable enough to allow accurate recataloguing at any time. In addition, of course, it must be simple and fast in operation, and allow changes in the standards with the minimum of time and effort.

One color-analysis apparatus which fulfills these qualifications utilizes the well-known principle of combining three colors to obtain white. This analysis method produces a standard color which will match the kinescope screen under test. It consists of projecting three colors onto the same spot on a comparison screen with means for controlling the intensity of each color so that a white, or any near-white color, which will be produced by an acceptable kinescope screen, can be matched.

Figure 1 shows an optical layout which allows the above operational features and utilizes only one light source. F is the filament of a suitable source, which is reinforced by a concave mirror M. L_1 is a projection condenser lens used to keep the light beam from deviating too much after passing through the three small condenser lenses L_2; L_1 and L_2 focus images of the source on the objective lenses, L_3. These images are slightly diffused by means of a ground glass diffusion plate P so that a fairly uniform illumination will be present at the objective lenses. This diffusion allows the alignment and stability of the optical system to be less critical and assures sufficient accuracy of duplication of color for the same objective-lens iris, I, settings. The fixed apertures, A, are so arranged that light from each L_2 lens will reach only one L_3 lens. Each L_3 lens is arranged in an eccentric manner with respect to its iris opening so that a prismatic effect is obtained to focus an image of L_2 in the center of the receiving screen, S. Thus images from all three L_3 lenses are superimposed on the receiving screen and any inexact superposition may be baffled by an appropriate mask, B. The color filters, C, are selected as the most appropriate tri-color combination to work with the chosen light source and to achieve maximum ease of manipulation for the color range required. Translucent screens will give the best results in this apparatus from the standpoint of efficiency, uniformity and freedom from stray light.

If the irises are made to be controlled through gears by three dials, it is necessary to set three dials for every color combination required. However, mechanical push-button arrangements may be utilized to set up any number of predetermined iris aperture combinations to give color intensities

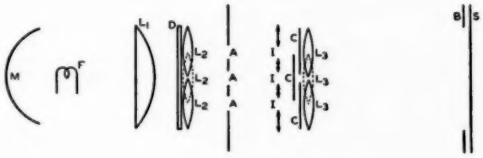


FIG. 1.

to match all acceptable kinescope screens. This arrangement allows the operator to obtain a matching color almost instantaneously. Furthermore, any given color is easily changed by means of screw-driver controls on each iris diaphragm adjustor. It might be found mechanically more simple to utilize a disk in front of the objective lenses instead of the irises. The periphery of this disk is perforated in such a manner that as it is rotated a different set of three apertures is aligned with the lenses. In order to avoid making a new disk every time the color standards must be changed, these apertures can all be cut to maximum lens areas, and the fixed apertures of the desired size can be slipped into place to obtain the correct standard color. This disk can be controlled directly with a step switch or by a single mechanical push-button control system.

The features of this apparatus are that its measurement of kinescope color eliminates guesswork, provides definite cataloguing for each individual tube, and minimizes the time and effort necessary to adjust color standards. Furthermore, it makes available reproducible data which can be utilized for controlling color variations before they become objectionable.

Erratum: Hue, Saturation, and Lightness of Surface Colors with Chromatic Illumination

(J. Opt. Soc. Am. **30**, 2 (1940))

In a paper of this title which appeared in the January, 1940 issue, the following correction should be made:

The $(L')^2$ term of Eq. (3) should read:

$$0.009 b_f (A_0 + \bar{A})(L')^2 \log_{10} 2000 I.$$

The shorter term given before by mistake applies to case 3 because by Eq. (5a): $A_f = (A_0 + \bar{A})/2$; but it does not apply to case 4 and was not used in the computations whose results were reported in tabular form.

Acknowledgment is due to Professor Harry Helson, Department of Psychology, Bryn Mawr College, who called attention to this error.

DEANE B. JUDD

National Bureau of Standards,
Washington, D. C.,
June 7, 1940.

A Complete Photoelastic Instrument

FRANK W. BUBB
Washington University, St. Louis, Missouri
(Received May 1, 1940)

THE figure shows an adaptation of Michelson's interferometer designed to provide a photograph of the contour lines (isopachics, or lines of constant principal stress-sum, $P+Q$) for any transparent plane test model under plane stress. The suggested instrument employs Faraday's effect, the magneto-optic rotation of light. Since the interferometer is a familiar instrument, we proceed to the theory of the present application.

A test model M of Bakelite or other transparent photoelastically sensitive material is held in one branch (No. 1) of the interferometer by a strain frame which subjects it to a given set of external forces. (See Fig. 1.) These forces induce a stress distribution in the model. It is the purpose of photoelasticity to analyze such stress distributions.

That portion of the plane polarized beam 1 which passes through a point of M where the principal stresses are P and Q, has its light vector E_1 resolved into two plane polarized parts p and q whose respective light vectors are parallel to P and Q. In passing through the model the beams p and q suffer alterations in optical paths due to two causes. In the first place, the model suffers a change δt in thickness given by the elastic law

$$\delta t = -(P+Q)\nu t/E.$$

Again, the respective refractive indices change in accord with the stress-optic law,

$$\mu_P = \mu + C_1P + C_2Q,$$
$$\mu_Q = \mu + C_1Q + C_2P,$$

where C_1 and C_2 are constants and μ is the refractive index of the unstressed model. The beams p and q suffer due to these two causes the optical retardations

$$\delta S_P = \mu_P(t+\delta t) - \mu t,$$
$$\delta S_Q = \mu_Q(t+\delta t) - \mu t.$$

Using the previous equations, these become

$$\delta S_P = (C_1P + C_2Q)t - (\mu + C_1P + C_2Q)\nu t/E,$$
$$\delta S_Q = (C_1Q + C_2P)t - (\mu + C_1Q + C_2P)\nu t/E.$$

After traversing the model M, both the p and q beams pass on into a "light rotator" R. One simple type of rotator amounts to a solenoid surrounding a tube of carbon disulfide. During its passage through the carbon disulfide, the light vector rotates in the direction in which the positive current flows in the solenoid—the law describing this phenomena being

$$\theta = VHL,$$

where θ is the angle through which the light vector rotates while traversing a length L of the medium along a magnetic field H, and V is Verdet's constant. H and L are so adjusted that the light vector rotates 45° while passing once along the axis of the solenoid. At the far end of the core, the light is reflected back by a mirror, rotates an *additional* 45°, and emerges with both p and q parts rotated 90° to their original directions.

Upon passing again through the model, the roles of the p and q parts are interchanged. The p part suffers the retardation δS_Q and the q part the retardation δS_P. Upon emerging from the model then, both parts p and q have the *same* retardation

$$\delta S = \delta S_P + \delta S_Q = (C_1 + C_2 - 2\mu\nu/E)(P+Q)t, \quad (1)$$

where a term of the order of 0.005 is neglected. Hence, the p and q parts recombine into a light vector E_1' at right angles to the original direction of the incident light vector E_1.

Beam 2 proceeds from the half-mirror H through the other branch of the interferometer and returns through the half-mirror to recombine with that part of the returning beam 1 which reflects from H. Since the light vectors E_1' and E_2 of corresponding parts of beams 1 and 2 are at right angles to each other, they will not, under ordinary circumstances, interfere. However, we interpose an analyzer A (between H and the screen S) having its axis at 45° to E_1' and E_2. This analyzer permits only those components to pass which are parallel to the axis of A. Hence

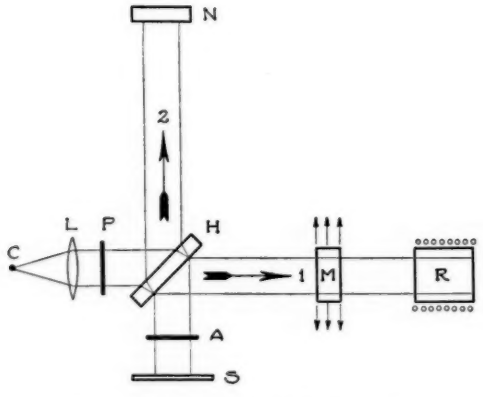


FIG. 1. Interferometer for isopachic lines.

those parts of beams 1 and 2 which pass on to S have parallel light vectors and will interfere.

Any slight difference in optical paths between beams 1 and 2 when the former passes through the unstressed model can be ignored, since by proper adjustment of the interferometer, they can be made to yield a uniform field (extinction, say) all over the screen. Hence when the model is stressed, δS, as given in (1), is the only part of the path difference between corresponding parts of beams 1 and 2 which needs be taken into account. When for any point of M, the relation $\delta S = m\lambda$ holds, m being an integer and λ the wave-length, the corresponding point on S will also show extinction. The locus of such points will cast a black fringe on S. For successive integral values of m, the screen will show successive black fringes—and these will be separated by bright (half-wave-length) fringes. Combining (1) with the equation $\delta S = m\lambda$, we find that

$$P+Q=Im, \tag{2}$$

where $I=\lambda/(C_1+C_2-2\mu\nu/E)t$ is a constant. The isopachic fringe constant I may also be found directly by a simple tension or bending test as is commonly done in measuring the isochromatic fringe constant.

For a Bakelite model 0.25″ thick, I turns out to be of the order of 100 psi per fringe for the double passage of light through the model. One can interpolate between adjacent fringes by eye to about 1/10 fringe (and to about 1/100 fringe with a Babinet compensator). This corresponds to an accuracy of about 10 psi with the unaided eye.

In a region of high isopachic gradient, a small spot of the model may be inclined to the incident light at such an angle that the beam is refracted away from its initial path so much that it may return from the rotator and pass through a different spot. Such action would cause a blurring of the isopachic fringes. This blurring effect, if it occurs, may be entirely eliminated by immersing the model in a liquid having the same index of refraction as the model—in which case the light would pass straight through. If the model be immersed, the above theory must be altered slightly—the end result being that $P+Q=I'm$ where $I'=\lambda/(C_1+C_2)t$. The numerical value of I' is about 80 psi per fringe for 0.25″ thick Bakelite and the isopachic pattern has more fringes with the bath than without. The bath also eliminates the necessity for careful polishing.

By obvious and trivial alterations the present instrument may—without disturbing the model—be converted into a reflection type of polariscope. Along the nth-order isochromatic fringe provided by such a reflection polariscope, the well-known relation

$$P-Q=kn \tag{3}$$

holds, where the isochromatic fringe constant k for 0.25″ thick Bakelite has about the value 150 psi per fringe.

The present instrument is capable, therefore, of giving both the $P+Q=Im$ pattern and the $P-Q=kn$ pattern. By simple addition and subtraction, we at once find the individual principal stresses

$$\begin{aligned} P&=(Im+kn)/2 \\ Q&=(Im-kn)/2. \end{aligned} \tag{4}$$

By removing the quarter-wave plates from the reflection polariscope arrangement, one may photograph the familiar isoclinic lines which yield the directions of the principal stresses.

Thus the proposed instrument provides a complete experimental solution for all problems of plane stress—the most important technical problem in both machine and structural design. For this reason, the new device may fairly be called a complete photoelastic instrument.

A Contrast Meter for Photographic Papers*

C. A. MORRISON
Kodak Research Laboratories, Rochester, New York
(Received April 17, 1940)

THE sensitometric characteristics of a photographic paper are best expressed by the D-log E curve, which, to the experienced observer, gives all the necessary information regarding it. It is common practice, however, for purposes of record and comparison, to express these characteristics in terms of a group of numerical values derived from the curve. The values usually desired are speed, exposure scale, maximum density, maximum gradient, and contrast. All of these except contrast can be easily derived from the graph of the sensitometric curve. The significance of the contrast value has become of major importance in the list of numerical values characterizing a photographic paper, but the laborious process of measuring it has prevented its general utilization. The instrument to be described here simplifies the procedure and makes the determination of contrast rapid and easy.

In a monograph on the contrast of photographic printing paper, Jones[1] proposed an expression for the numerical evaluation of the contrast of photographic papers. According to this expression, the contrast capacity of a photographic developing-out paper is determined by two factors, a rate factor and an extent factor. The rate factor is $dD/d \log E$ and the extent factor is measured by the density range of the paper. The value of contrast in absolute terms of the sensitometric characteristics is expressed in the form

$$\Omega = \frac{(D_{\max} - D_{\min}) \cdot [\bar{G}(D)]}{l\Delta D^2},$$

in which $\bar{G}(D)$ is the average gradient computed in terms of equal density increments rather than in terms of equal log exposure increments, and $l\Delta D$ is the smallest density difference which the eye can discriminate under average print-viewing conditions, i.e., approximately equal to 0.007.

In practical photographic paper sensitometry it has been found[2] that contrast is directly proportional to log Ω as judged by the visual evaluation of contrast differences between prints. On this basis, papers between which the difference of log Ω values is the same will appear to be of the same order of contrast difference when viewed as prints from the same negative or, conversely, will produce prints of similar contrast from a series of negatives of equal and complementary contrast separation. A series of papers of different contrasts whose log Ω values change successively by equal amounts will appear to change in contrast by equal steps and is considered as a well-balanced series of papers.

In order to apply the method of contrast evaluation to practice, the following procedure is carried out: From the sensitometric curve (Fig. 1) the $dD/d \log E$ value (slope) is determined for each 0.1 unit of the density scale. Each of the slope values for the corresponding points on the curve is plotted against its density value as shown in Fig. 2. The area under this curve is then determined by measurement with a planimeter. According to the derivation, this area is directly proportional to contrast, and when the area is multiplied by a suitable factor, the result is expressed in terms of units of a convenient scale.

The new instrument, shown in Fig. 3, performs these steps mechanically, while the operator scans the sensitometric curve with the viewing head H. At the end of the scanning cycle, the value of Ω (contrast) appears at the index of the scale drum of the planimeter, which is incorporated in the instrument.

The principle of the instrument is illustrated by Figs. 3 and 4, which are similar in viewpoint and lettering. A small portion of the sensitometric curve D is viewed through a 15-degree biprism, base down, at the bottom of the tube B. The tube and the arm A rotate about the axis T (Fig. 4) as a unit. When the line dividing the two isosceles

* Communication No. 759 from Kodak Research Laboratories.

[1] L. A. Jones, "The contrast of photographic printing paper," J. Frank. Inst. **202**, 177 (1926); **203**, 111 (1927); **204**, 41 (1927).

[2] L. A. Jones and C. A. Morrison, "Sensitometry of photographic papers," J. Frank. Inst. **228**, 445–470, 605–622, 755–769 (1939).

faces of the prism is normal to the part of the curve under observation, the curve, as viewed through the tube, will appear continuous, while, if it is not normal, the curve will appear discontinuous, as illustrated in Fig. 4. Then, if during the scanning of the curve, the position of the prism is adjusted to make the portion of the curve within the field of the prism appear continuous, the angular displacement of the arm A at any particular point of the curve will be a measure of the angular position of the tangent of the curve at that point.

The function of the mechanism in the viewing carriage H is to convert the angular displacement of the arm A into a linear displacement of R which is proportional to the tangent of the curve. As the prism tube B and slotted arm A rotate, the roller R, within the slot, is so held that it can move only in the direction EW. When the axis of the slot is coincident with the line CC, the roller R occupies the position P. This position corresponds to the setting for zero slope of the curve and the prism is adjusted to show the abscissa as a continuous line. For any slope greater than zero, we can construct triangles TRP (Fig. 4) with the side TP constant. Angle RTP is a measure of the slope of the curve D at point T with respect to the abscissa, when the curve appears continuous in the field, and, since $\tan RTP = RP/TP$ and TP is constant, RP is proportional to the tangent of the angle. The value of the tangent is therefore measured by the displacement along EW of R from P.

The rotation of the prism is controlled by the knob K acting through the shaft, worm, and rack. The worm is keyed to rotate with the shaft in such a manner as to provide freedom of motion along the shaft. This lateral motion causes no mechanical movement of the rest of the system, but makes it possible to follow the curve D with the optical tube B. At the right end of the shaft, and enclosed in the large housing F, another worm is fixed to the shaft. This worm and its rack are duplicates of the pair in H. The distance from the NS axis to the point N to which the tracer head of the planimeter is attached corresponds exactly with the displacement of the roller axis R from P. A typical path followed by N, when the curve is scanned, is shown by the dashed line (Fig. 4). This line represents $dD/d \log E$ of the curve D plotted as a function of density, as shown in Fig. 2.

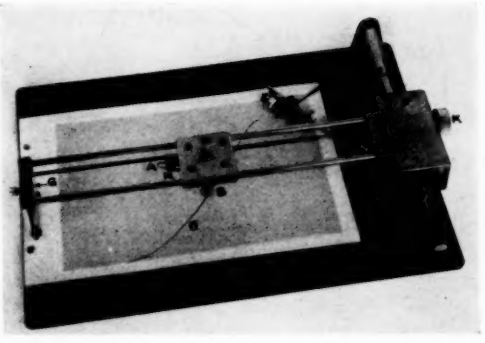
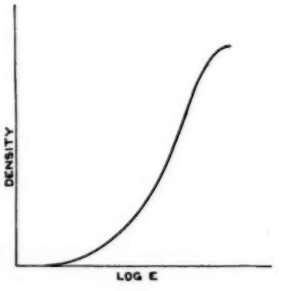


FIG. 3. Plan view of contrast meter for photographic papers.

After the curve is scanned and the planimeter head is returned to the position S, the area under the dashed-line curve is indicated by the planimeter drum index. This area multiplied by an appropriate factor gives the value of contrast on the desired scale. The instrument is shown with the curve drawn to the scale on which unit $\log E$ equals 5 inches, unit D_R equals 5 inches, and with the planimeter set for one unit on the drum to equal 80 sq. mm. These scale magnitudes make unit drum reading equivalent to unity on the contrast scale proposed by Jones. By adjusting the planimeter or by using a suitable factor, curves drawn to other scales can be measured.

The base of the instrument is a metal plate 23 inches by $16\frac{1}{4}$ inches by $\frac{1}{4}$ inch, on which is mounted the $\frac{3}{4}$-inch rod L, which serves as a rail along which the entire mechanism is guided in



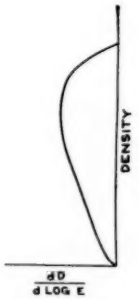


FIG. 1 (left). Typical sensitometric curve of a photographic paper.
FIG. 2 (right). Curve showing relationship between $dD/d \log E$ and density.

the direction *NS* upon rollers in housing *F*. Projecting to the left from this housing are two $\frac{3}{8}$-inch guide rails, upon which the carriage *H* moves. The bearings within this housing *H* consist of four grooved rollers whose axes are indicated by the four black screw heads on the cover plate. A plate is attached to the left end of the small rails. This has rollers which rest on the base. The entire mechanism can be rotated in a vertical plane around the large rail by lifting the left end plate to insert the graph sheets. The anchor disk of the planimeter may be placed at any convenient position on the base plate.

The instrument is provided with a calibrated dial *G* on the inner side of the left-hand end plate. This dial indicates the maximum slope (G_{max}) of the curve attained during a scanning cycle. It is connected through gears to the control shaft. The dial is turned by the mechanism to its maximum position by a projecting pin on its shaft. When the direction of rotation is reversed as the inflection point of the curve is passed, the dial is left until reset to zero position by hand after the reading is taken. This dial also serves to adjust the prism in its cell during calibration against a chart of lines with known slopes.

The entire mechanism is very precisely made and fitted so that the moving parts can be easily controlled and operated. The planimeter is a standard model to which has been fitted a ball head on the guide pin axis. The ball fits into a spring socket at *N* on the right-hand rack.

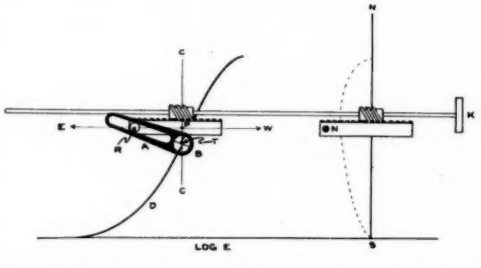


FIG. 4. Diagrammatic plan view of mechanism of contrast meter.

To operate the instrument, the curve is first inserted and aligned, with its axes parallel to the mechanical axis of the instrument. With properly punched coordinate paper, this is accomplished by placing the perforations over the pins in the base. Various sets of holes for the pins are provided for the best placing of the curve. The lowest density abscissa of the curve is centered within the field of the prism and the index on the planimeter drum is set to zero. The right hand is placed on the knob *K* and the left hand guides the viewing head *H*. While the curve is viewed through the tube *B*, it is followed from toe to shoulder by the resultant motion of the two heads, and the right hand so turns the knob that continuity of the curve is maintained in the viewing field. When the curve is completely scanned, the right-hand housing is returned to the minimum density position. The reading of the index of the planimeter drum completes the measurement. A little practice quickly establishes the desired coordination between the hands and the eye. It is desirable to make three scannings of the curve without resetting the planimeter drum. A reading is taken after the first cycle, which then serves as a check on the final result, which is one-third of the total reading from the planimeter.

The procedure just described measures the total contrast capacity of the paper. This assumes that the total density range in the print is utilized. If the density range of the print is less than the maximum density of the paper, only a part of the total contrast is used. This partial amount may be measured with the instrument by scanning that part of the curve which lies between the limiting densities of the print, and then returning the mechanism to the level of the minimum density. The partial contrast utilized is read from the planimeter drum.

Experience obtained from comparison of instrumental measurements with graphical measurements indicates that the probable difference of the results of the two methods is no greater than plus or minus one percent.

Triboluminescence of Sugar

FRANCES G. WICK
Vassar College, Poughkeepsie, New York
(Received February 7, 1940)

THE triboluminescence[1] of sugar is a well-known phenomenon.[2–5] All forms of crystalline sugar including rock candy, granulated sugar and various kinds of sugar wafers emit light when broken or ground in a mortar. That this light is due, at least in part, to electric discharges which take place when the crystals are broken has been shown by different observers. Longchambon[6] made a photographic study of the spectrum of the tl light emitted by sugar and he found many of the ultraviolet bands of nitrogen, indicating that there is an electrical discharge in air when the crystals are broken. He observed also that the light emitted is of greater intensity when the sugar is broken in a tube at reduced pressure—between 4 and 0.1 cm of mercury. This is to be expected of an electric discharge in air. Longchambon[7] found that other substances, such as cadmium sulphate, uranium nitrate, and calcium fluoride show nitrogen bands in their tl spectra when the materials emitting the TL are surrounded by air at normal pressure. Accompanying the nitrogen bands and, in some cases much stronger than these, is the characteristic band fluorescence spectrum of the material broken. Harvey[8] observed that when some nontriboluminescent substances are shaken or crushed in a 5-cm atmosphere of neon gas, reddish electrical discharges characteristic of the neon may be observed. He also found that many substances which are tl in air at ordinary pressures show only their characteristic TL in an atmosphere of neon with no trace of the red color of the neon gas. Other substances including rock candy crystals, show, when broken in a neon atmosphere, the reddish light of neon and also the color characteristic of the material itself as seen when the substance is surrounded by air or other media, indicating that part of the light is caused by an electric discharge in neon and part is due to some source within the material itself.

Harvey found that light is emitted by sugar when it is broken under liquids indicating that the electric discharge in the gas surrounding the sugar is not the only source of the light in the TL of sugar. This verifies the observations made by Wick[9] that, in the emission of TL there are three factors one or more of which may be present in any given case. Harvey[10] has recently observed that the intensity of the light emitted by various sugar candy wafers when they are broken varies with the flavor of the candy, wintergreen being the brightest of the common flavors. His conclusion is that wintergreen which is fluorescent under the excitation of an ordinary spark, is excited by the tl light from the sugar itself or by the electrical discharge which takes place when the sugar is broken. This fluorescence is added to the other emissions when the sugar wafer is broken.

The work of Harvey[8,10] suggested to the author some further experiments upon the TL of sugar. Experiments were made to determine the effect of adding to sugar crystals various fluorescent materials such as oils and dyes which are known to be excited by an ordinary spark. Since, as is well known, the luminescence excited by the spark and other sources is, for many substances, more intense at low temperatures than at room temperature, experiments were made down to the temperature of liquid air to see whether or not there might be an increase in the intensity of TL at low temperatures, in cases in which the excitation by the iron spark is more effective at these low temperatures. This should be true according to the assumptions of Harvey that the tl is due at least in part to a spark discharge when the crystals are broken.

[1] In this paper the abbreviations suggested by Imhof are used as follows: triboluminescence—TL, triboluminescent—tl.
[2] Kayser, *Handbuch der Spectroscopie*, Vol. IV, p. 838.
[3] A. Imhof, Physik. Zeits. **18**, 78 (1917).
[4] Th. Steel, Nature **59**, 295 (1899).
[5] Burke, Nature **58**, 533 (1898).
[6] H. Longchambon, Comptes rendus **174**, 1633 (1922).
[7] H. Longchambon, Comptes rendus **176**, 691 (1923).
[8] Harvey, Science **89**, 460 (1939).
[9] F. G. Wick, J. Opt. Soc. Am. **27**, 275 (1937).
[10] Harvey, Science **90**, 35 (1939).

Excitation by an Iron Spark

Since various experimenters[4–6] have assumed that an electric spark emitted when crystals of sugar are broken is a factor in the TL, the effect of a spark discharge between iron terminals of the secondary of a transformer in exciting luminescence in sugar was observed at different temperatures down to that of liquid air. TL was also observed at these same temperatures in an attempt to discover what part of the TL emitted at various temperatures when sugar is cracked or broken is due to luminescence excited by a spark emitted by the sugar itself when the crystals are broken. It was thought that a lowering of the temperature and the addition of a luminiscent material both of which increase the intensity of luminescence under the iron spark should increase the intensity of TL due to excitation by an electric discharge which takes place when the sugar crystals are broken.

Pure sugars

Crystals of cane sugar are dimly phosphorescent after exposure to the iron spark at room temperature and much more strongly so after exposure at liquid-air temperature. The color of this low temperature phosphorescence is blue and the spectrum is a broad band between 4200 and 5500A. Maltose sugar shows phosphorescence under the spark at room temperature and phosphorescence of higher intensity at liquid-air temperature. The color of this emission is greener than that of cane sugar and the spectrum extends from approximately 4400 to 5500A. Lactose sugar is excited to phosphorescence which is dim at room temperature and much brighter at the temperature of liquid air. Cane sugar, maltose and lactose show TL at room temperature and TL of increased intensity at the low temperatures at which the sugars are all more highly phosphorescent when excited by the iron spark. It was observed that the TL of all the sugars is dependent upon the dryness of the material. Crystals exposed to the air during the summer when the humidity is high show much less intense TL at room temperature than those kept in a desiccator.

Caramelized sugar which is noncrystalline, and is in a vitreous or amorphous state shows phosphorescence at room temperature and a much brighter phosphorescence at liquid-air temperature but shows no TL at any temperature. In order to show TL sugar must be in the crystalline state but phosphorescence is not dependent upon the state of crystallization.

Sugars to which oils have been added

Since oil of wintergreen causes an increase in the brightness of light emitted when crystals of sugar are ground,[8, 10] it seems reasonable to expect that other oils which are excited to fluorescence by the spark will produce a similar effect. Oils of anise, bergamont, cedar, citronella, clove, eucalyptus, geranium, lavendar, lemon, muellin, organum, peppermint, pine needles, rose geranium and wintergreen were found to show no luminescence excited by the spark when they are in the liquid state. They solidify at different temperatures when cooled in liquid air and, in the solid state, some are excited to luminescence by the spark and some are not. Oils of wintergreen, bergamont, clove, lemon, lavendar, sassafras, peppermint and organum show fluorescence or phosphorescence or both in varying degrees under spark excitation; the others show practically none.

Sugar candy wafers of different flavors are excited to dim phosphorescence at room temperature by the iron spark and to a much stronger emission at low temperatures whether the wafers are made of crystalline or caramelized sugar. The intensity of luminescence varies with the flavor of the candy.

It was found, in general, that oils which, in the solid state show luminescence under the iron spark, the brightest of which are wintergreen and bergamont, give to sugar crystallized from solutions containing these oils and to sugar candies the same kind of luminescence due to spark excitation as that exhibited by the solidified oils themselves. Caramelized, amorphous sugar shows no TL. Crystalline sugar shows TL which is increased in intensity by the addition of any oil which itself is fluorescent under the spark and the intensity of TL is observed to be greatest at those temperatures at which the fluorescence of the oil is most highly excited by the spark. Some oils which increase the phosphorescence but not the

fluorescence of sugar are not effective in intensifying TL.

It was found that sugar crystals and candy crystalline wafers flavored with fluorescent oils such as wintergreen emit a brighter tl light when ground under acetone or heavy mineral oil than pure sugar crystals or wafers flavored with some oil such as peppermint which is excited to phosphorescence and not fluorescence when exposed to the spark.

Sugars to which luminescent dyes have been added

Dyes which are fluorescent in water solution including uranine, amino *G* salt, naphtha sultam and other duPont products, added to the solutions from which sugar was crystallized were found to cause the sugar crystals thus formed to be fluorescent under the spark at the same temperatures at which the water solutions of the same dyes are excited to fluorescence as indicated by previous observations.[11] The addition to sugar crystals of dyes which, in water solution, are fluorescent under ultraviolet light increases the intensity of TL at those temperatures at which the fluorescence is excited by an external source.

Sugar to which anthracene has been added

Finely divided anthracene, a solid which is fluorescent under the iron spark, was put into a solution of cane sugar from which crystals were formed. Specks of anthracene were observed through the crystalline mass of sugar which were excited to fluorescence under the iron spark. The TL of the sugar crystals containing this anthracene was found to be stronger than that of pure sugar.

Carbohydrates

It is of interest to note that carbohydrates, including the closely related groups of sugars, starches, and cellulose, are all phosphorescent after exposure to the spark and that this phosphorescence is greatly intensified by the lowering of temperature but, of the group, only the sugars which are crystalline are tl. Different kinds of rayon such as viscous rayon, cellulose, acetate rayon, and cupric rayon and also cotton, wool and silk are all phosphorescent at liquid-air temperature and show little or no phosphorescence at room temperature.

[11] F. G. Wick and C. G. Throop, J. Opt. Soc. Am. **25**, 368 (1935).

Light Emitted When Sugar Crystals are Suddenly Cooled or Heated

During the progress of these experiments it was observed that crystalline sugar wafers emit light when they are dropped into liquid air. This is true of any mass of crystalline cane sugar such as rock candy and also of maltose and lactose sugars. The sudden change of temperature cracks the crystals and light appears to be emitted as in the case of mechanical fracture. This light is not bright and the eyes should be dark adapted for approximately ten minutes to see it well.

Sugar flavored with oil of wintergreen or some other fluorescent substance emits a brighter light when dropped into liquid air than that emitted by pure sugar. When half of the surface of a sugar wafer is wet with oil of wintergreen or bergamont and the wafer is suddenly cooled by plunging it into liquid air the half covered with the fluorescent oil emits a much stronger light than the other half. A flickering light is emitted from the oil indicating that it is excited to luminescence by something in the nature of sparks which occur intermittently when cracks occur in the crystals. This scintillating light may be observed more distinctly through a magnifying glass.

When crystals of sugar are suddenly warmed after being reduced to the temperature of liquid air there is an emission of light. When a cube of granulated sugar tied to a string is lowered into liquid air it emits light while it is cooling and the emission stops when the temperature becomes constant. When the specimen is suddenly removed from the liquid air there is an emission of light upon warming, the intensity of which increases with an increase in the speed of warming. The light emitted upon warming as well as that emitted upon cooling is much more intense in a cube of sugar saturated with oil of wintergreen than in a cube of pure cane sugar, and is of a scintillating nature. Wintergreen Necco wafers emit light upon warming from liquid-air temperature to that of the room and this light is greatly increased in intensity by pouring oil of wintergreen over the wafer before cooling it.

A concentrated solution of cane sugar in distilled water emits faint scintillating light while the solution is freezing and before the temperature becomes constant. Upon warming from liquid-air temperature up to the temperature at which the solution again becomes liquid a similar faint light is emitted. In a saturated sugar solution containing oil of wintergreen the light emitted upon cooling to liquid-air temperature and again upon warming is much more intense than in the case of the pure sugar solution.

The phenomenon of the emission of light when a crystal mass is dropped into liquid air may be observed more strikingly in the case of uranium nitrate.[12] Dewar[13] and Becquerel[14] observed such an emission when crystals of uranium nitrate are suddenly dropped into liquid air and also when these crystals are suddenly warmed from this low temperature to that of the room. The author observed that the emission of light upon cooling uranium nitrate crystals in liquid air and also upon warming them from liquid-air temperature to that of the room is brighter than the corresponding emission in the case of pure sugar or even sugar containing oil of wintergreen. Precht[15] points out that this relatively strong light is due to the cracking of the crystals and to the increase in the intensity of fluorescence of uranium nitrate under the spark at low temperatures. Dewar[13] holds that the lighting and cracking of the crystals is an electric phenomenon. He says that when crystals such as uranium nitrate and the platino-cyanides are dropped into liquid air or hydrogen there is an electric stimulation brought about by sudden cooling and actual discharge takes place between the molecules of the crystals. Both liquid air and liquid hydrogen are highly insulating and a discharge taking place under such circumstances proves that the potentials are high. Although the density of uranium nitrate is 2.8 and that of the liquid about 1, such a crystal refuses to sink because it becomes charged and sticks to the sides of the vacuum vessel. A marked pull on the silk thread holding it is required to detach it. He also observed that such a crystal removes cloudiness from the liquid air by attracting to itself suspended particles. Precht[15] suggests that this phenomenon may be explained as a simple case of pyroelectric effect according to which a crystal, during warming or cooling acquires a charge and continues to hold this charge in an insulating medium. It may also be explained as a piezoelectric effect due to molecular changes upon sudden expansion and contraction.

[12] F. G. Wick, J. Opt. Soc. Am. **29**, 407 (1939).
[13] J. Dewar, Nature **64**, 244 (1901).
[14] H. Becquerel, Comptes rendus **133**, 199 (1901).
[15] Precht, Physik. Zeits. **3**, 457 (1902).

Observations on Ice

During the course of these experiments ice crystals condensed upon the outside of the mortar containing liquid air. This mortar was exposed to the iron spark, and it was observed that the ice crystals showed phosphorescence at temperatures almost down to that of liquid air. Ice from a cooler was found to be phosphorescent at this low temperature, as was ice made by pouring water into liquid air or by freezing distilled water in an electric refrigerator. Ice at this low temperature is also found to be triboluminescent, emitting light when ground in a cold mortar. The intensity of this light is increased by exposing the ice to the spark at a low temperature before grinding. The results previously given upon a frozen solution of naphtha sultam show the same effect. The water solution is tl at a low temperature and this TL is markedly increased in intensity by exposure to the spark.

The phosphorescence of ice has been previously observed by some experimenters[16] and questioned by others. Armstrong[17] says that Sir James Dewar found that pure water frozen is phosphorescent and water from a tap is not. Precht[15] suggests that the TL of ice upon cooling may be considered to be a pyroelectric effect or a piezoelectric effect due to molecular changes in sudden expansion or contraction.

Summary

(1) When crystals of sugar are ground or cracked so that they show TL there is an electric discharge in the air or other gaseous medium which fills the space between the parts of the crystals broken. A part of the tl light is due directly to this discharge.

[16] Kayser, *Handbuch der Spectroscopie*, Vol. IV, pp. 636, 686, 832.
[17] Armstrong, Nature **113**, 163 (1924).

(2) The addition of fluorescent oils or dyes to a crystalline mass of sugar causes an increase in the intensity of TL due to the fact that fluorescence in the oil or dye added is excited by the spark emitted when the crystals are broken thus making the total emission of light greater. The TL is strongest at those temperatures at which the fluorescence of the oils and dyes added is strongest when excited by the iron spark.

(3) The discharge in air is not the only source of excitation of fluorescent oils or dyes added to sugar as is indicated by the fact that the addition of such oils and dyes increases the intensity of TL when the sugar crystals containing them are ground under liquids.

(4) Crystals of sugar emit light upon sudden change in temperature such as is brought about by dropping them into liquid air and by suddenly withdrawing them from liquid air. This emission is increased in intensity by the addition of fluorescent oils or dyes to the solutions from which the crystals are formed.

(5) Ice is phosphorescent and tl at low temperatures. The intensity of this TL is increased by exposure of the ice to the iron spark at a low temperature before grinding it.

This work confirms the general assumptions made by Wick[9] that one or more of the following factors may be present in the emission of TL in any given case: (a) an emission which resembles phosphorescence and thermoluminescence. This may be increased in intensity by exposure to sources of excitation such as radium, x-rays and the iron spark. (b) Emission characteristic of the material itself, not dependent upon previous excitation. (c) Emission due to an electric discharge in the gas surrounding the crystal when it is broken. These experiments verify also the explanation of Harvey[8,10] that the addition of a fluorescent substance such as oil of wintergreen to sugar wafers increases the intensity of TL because the oil is excited to fluorescence by an electric discharge which takes place between the parts of the sugar crystals when they are broken and also by an emission from the sugar itself.

The author wishes to express her appreciation to the Department of Physics of Cornell University for generously giving the facilities of the laboratory of physics for this work and to Mabel Slattery Vincent for help and suggestions. Grateful acknowledgment is made of assistance given by grants for the purchase of apparatus from the Rumford Fund of the American Academy of Arts and Sciences and from the Beadle Research Fund of Vassar College.

Normal Systems with Two Caustic Lines*

M. HERZBERGER
Kodak Research Laboratories, Rochester, New York
(Received April 18, 1940)

IT has been called to my attention by Dr. T. Yamasita and S. Jemura from the Nippon-Kogaku Research Laboratory that in my paper, "Normal systems with two caustic lines"[1] (hereafter abbreviated N.S.), one possibility was overlooked, namely a normal system exists consisting of the lines connecting an ellipse and a hyperbola in two planes orthogonal to each other and having one common axis. A further restriction which these authors make, that the vertex of one curve and the focal point of the other coincide, is unnecessary. I take this opportunity to thank them for calling this point to my attention and I shall at the same time make some additional remarks which may be of interest.

We let $\mathbf{b}(v)$ and $\mathbf{a}(u)$ be two curves. We have pointed out that the necessary and sufficient conditions, that the connecting lines form a normal system, are the existence of two functions $\phi(u)$ and $\psi(v)$ (sign of ψ changed from N.S.) such that

$$[\mathbf{b}(v)-\mathbf{a}(u)]^2=[\phi(u)-\psi(v)]^2. \tag{1}$$

This is Eq. (9 N.S.). Differentiation of (1) according to u and v gives the other fundamental formulae of our paper (10 N.S.) and (20 N.S.) which can be written

$$\mathbf{b}_v\mathbf{a}_u=\phi_u\psi_v \tag{2a}$$

or, if neither ϕ nor ψ is constant,

$$(\mathbf{b}_v/\psi_v)\cdot(\mathbf{a}_u/\phi_u)=1, \tag{2b}$$

where the suffix designates differentiation according to u and v, respectively. Eq. (1) shows that ϕ and ψ are given except for an additive constant. To see their geometrical meaning, we introduce the unit vector $\mathbf{s}(u, v)$ along the rays and then have (correcting the misprint ξ instead of $\mathbf{s}$ in (8 N.S.))

$$\mathbf{b}(v)-\mathbf{a}(u)=[\phi(u)-\psi(v)]\mathbf{s}(u, v), \tag{3}$$

or

$$\mathbf{b}(v)+\psi(v)\mathbf{s}(uv)=\mathbf{a}(u)+\phi(u)\mathbf{s}(uv)=\mathbf{w}(uv). \tag{4}$$

We now show that $\mathbf{w}(uv)$ is a wave surface of the normal system, and that it is the general wave surface, if we allow an additive constant in $\psi(v)$ and $\phi(u)$. We find by differentiating the first Eq. (4) with respect to u

$$\mathbf{w}_u\cdot\mathbf{s}=\mathbf{s}_u\cdot\mathbf{s}=0, \tag{5}$$

because $\mathbf{s}$ is a unit vector. In differentiating the second with respect to v, we find

$$\mathbf{w}_v\mathbf{s}=\mathbf{s}_v\mathbf{s}=0 \tag{6}$$

or, $\mathbf{w}$ is a wave surface.

Inserting (3) in (4), we obtain for the wave surfaces the equation

$$\mathbf{w}(uv)=(\phi\mathbf{b}-\psi\mathbf{a})/(\phi-\psi), \tag{4a}$$

where we still can add an arbitrary constant to ϕ and ψ.

Now, let us go back to the analysis of (2). The case that ϕ or ψ is constant has been correctly analyzed in N.S. We find there that one of the curves must be a straight line and the other must be a circle in a plane perpendicular to the straight line. The wave surfaces are toric surfaces.

We must consider next formula (2b). For the time being, let us set

$$\mathbf{b}_v=\chi_v\mathbf{B}(v), \quad \mathbf{a}_u=\chi_u\mathbf{A}_u. \tag{7}$$

We have

$$\mathbf{A}(u)\cdot\mathbf{B}(v)=1: \tag{8}$$

two vector functions, the product of which is unity. The geometrical discussion of this case in the first paragraph, page 393 (N.S.), is incomplete. We can conclude only that the end points of the vectors $\mathbf{A}$ and $\mathbf{B}$ lie in two planes orthogonal to each other. If we choose three Cartesian unit vectors $\mathbf{i}$, $\mathbf{j}$, and $\mathbf{k}$ such that $\mathbf{k}$ is in the intersection line of the two planes, $\mathbf{i}$ and $\mathbf{j}$ in the first and second planes, respectively, we can write

$$\begin{aligned}\mathbf{A}&=\mathbf{a}_u/\phi_u=x(u)\mathbf{i}+C\mathbf{k}\\ \mathbf{B}&=\mathbf{b}_v/\psi_v=y(v)\mathbf{j}+\mathbf{k}/C,\end{aligned} \tag{9}$$

where C is a constant and x and y are arbitrary functions of (u) and (v), respectively. By choosing

* Supplement to Communication No. 734 from the Kodak Research Laboratories. J. Opt. Soc. Am. **29**, 392, 1939.
[1] M. Herzberger, J. Opt. Soc. Am. **29**, 392–394 (1939).

the origin conveniently, we can integrate (9) and obtain

$$\begin{aligned}\mathbf{a}&=X(u)\mathbf{i}+(C\phi+D)\mathbf{k}\\ \mathbf{b}&=Y(v)\mathbf{j}+(\phi/C-D)\mathbf{k},\end{aligned}\tag{10}$$

where $X(u)$ and $Y(v)$ are arbitrary functions, but C and D are constants.

Equation (10) gives a solution of the problem only if (1) is fulfilled. That gives us a connection between ϕ and X (ψ and Y), and thus the Cartesian equation of the problem (1) can be found.

We find from (10) that

$$X(u)^2+Y(v)^2+\left(C\phi-\frac{1}{C}\psi+2D\right)^2 =[\phi(u)-\psi(v)]^2,\tag{11}$$

or

$$X(u)^2+(C^2-1)\phi(u)^2+4DC\phi(u)+2D^2 =-\left[Y(v)^2+\left(\frac{1}{C^2}-1\right)\psi(v)^2 -\frac{4D}{C}\psi(v)+2D^2\right].\tag{12}$$

The right side of (12) is a function of u, and the left side is a function of (v). This is possible only if both sides are constant $(=E)$. Let us now insert in (12) from (10)

$$\begin{aligned}C\phi+D&=z(u)\\ (1/C)\psi-D&=Z(v).\end{aligned}\tag{13}$$

We find the equations

$$X^2+\left(\frac{C^2-1}{C^2}\right)(z-D)^2 +4D(z-D)+2D^2=E$$

and (14)

$$Y^2+(1-C^2)(Z+D)^2 -4D(Z+D)+2D^2=-E.$$

Let us assume that $C>1$ and $E>0$. Then, the first Eq. (14) is the general equation of an ellipse, one axis of which coincides with the Z axis. The second equation is that of a general hyperbola, also with one axis on the Z axis, in a plane orthogonal to that of the ellipse. For $C<1$ and $E<0$, the first equation is that of a hyperbola, and the second, of an ellipse.

For $C=1$ we get

$$\begin{aligned}X^2+4D(z-D)&=E-2D^2\\ Y^2-4D(z-D)&=-E-2D^2.\end{aligned}\tag{15}$$

Both curves are parabolas having a common axis.

The case, treated earlier, in which ϕ and ψ are constants, is contained in (14) as a special case if we set either

$$\begin{aligned}C&=0,\\ z&=D,\\ Y^2+(Z-D)^2&=2D^2-E,\end{aligned}\tag{16}$$

or

$$\begin{aligned}C&=\infty,\\ X^2+(Z+D)^2&=E-2D^2,\\ Z+D&=0.\end{aligned}\tag{17}$$

Optimum Efficiency Conditions for White Luminescent Screens in Kinescopes*

H. W. LEVERENZ
Research and Engineering Department, RCA Manufacturing Company, Harrison, New Jersey
(Received May 3, 1940)

Calculations based on energy ratios and relative luminosities of complementary colors show that the efficiency of white-light production is greatest for the pair of spectral lines at 4590A (violet blue) and 5720A (yellow green). Spectral distribution curves of relative absorption and emission are given for the zinc-cadmium sulphide phosphor systems and for typical white kinescope screens.

IN previously published papers,[1,2] information has been given concerning methods of producing efficient kinescope (television cathode-ray tube) screens, and data have been given indicating the wide range of colors now available in several phosphor systems.

Kinescopes used in the early stages of electronic television had green-emitting screens of manganese-activated zinc orthosilicate (willemite) or copper-activated zinc sulphide. A gradual evolution from green to yellow to cream (or sepia) to white took place as luminescence research, sponsored by television, brought forth efficient phosphors in regions of the visible spectrum other than those occupied by the original greens.

A brief summary of the color variations produced in the silicate and sulphide phosphor systems is given in Sections 3c–3d of reference 2. The more efficient phosphors are characterized by relatively narrow emission bands which produce rather saturated hues. The silicate system yielded the only homogeneous white-emitting phosphor known to the writer.[3] Unfortunately, the white-emitting silicates suffered too great a loss of efficiency by being spread not only over the visible spectrum but also over part of the ultraviolet region. The problem of efficient white-light production from kinescopes, therefore, was solved by mechanically mixing two or more phosphors to give a resultant broad emission spectrum.

Figure 1 shows the relative spectral distributions of energy for representative members of the silver-activated zinc-cadmium sulphide system.* The lower curves are for energy distribution while the upper curves are obtained by multiplying curves 1, 4, and 6 with the eye sensitivity values to obtain the relative visual stimuli represented by the area under each curve. The visual ineffectiveness of the strong blue-emitting zinc sulphide (curve 1) relative to the weaker yellow zinc-cadmium sulphide (curve 4) is occasioned by the former's greater distance from the maximum (5560A) of the eye sensitivity curve. Area-integration of the visibility-corrected curves gives good agreement with readings taken independently with an eye-corrected Weston photronic illuminometer (model 603), as is seen in the upper table of the figure.

It is obvious that the entire visible spectrum may be encompassed in infinitesimal gradations by the sulphide system alone. However, before considering the mixing of these phosphors to produce less saturated colors by addition, their absorption spectra shown in Fig. 2 should be considered. The method of making these absorption measurements of phosphor powders is also illustrated in the figure. The method of focusing the light into the monochromator entrance slit

* Presented before the Niagara Falls Meeting of the Optical Society of America, Oct. 27, 1938.

[1] H. W. Leverenz, J. Opt. Soc. Am. **27**, 25–35 (1937).

[2] H. W. Leverenz and F. Seitz, J. App. Phys. **10**, 479–493 (1939).

[3] H. W. Leverenz and F. Seitz, J. App. Phys. **10**, 491, and Fig. 27 (1939).

* The marked deviation of curve 2, ZnS(80) CdS(20):Ag, from the rest of the family of curves is evidently real. Repeated syntheses and tests give the same sub-normal result which is probably caused by a transition point in the zinc sulphide system's crystal structure. The ZnS:Ag phosphor of curve 1 shows both sphalerite and wurtzite structure while curves 3–7 of (ZnCd)S:Ag and CdS:Ag show only the wurtzite form. The ZnS(80) CdS(20):Ag phosphor therefore represents a strain point with respect to the definite crystallization which is necessary for high efficiency phosphors. The curve maximum of ZnS(90) CdS(10):Ag phosphor at 4700A is about 60 percent of the maximum of curve 2. Further investigations, including x-ray diffraction studies, are being undertaken in this anomalous region.

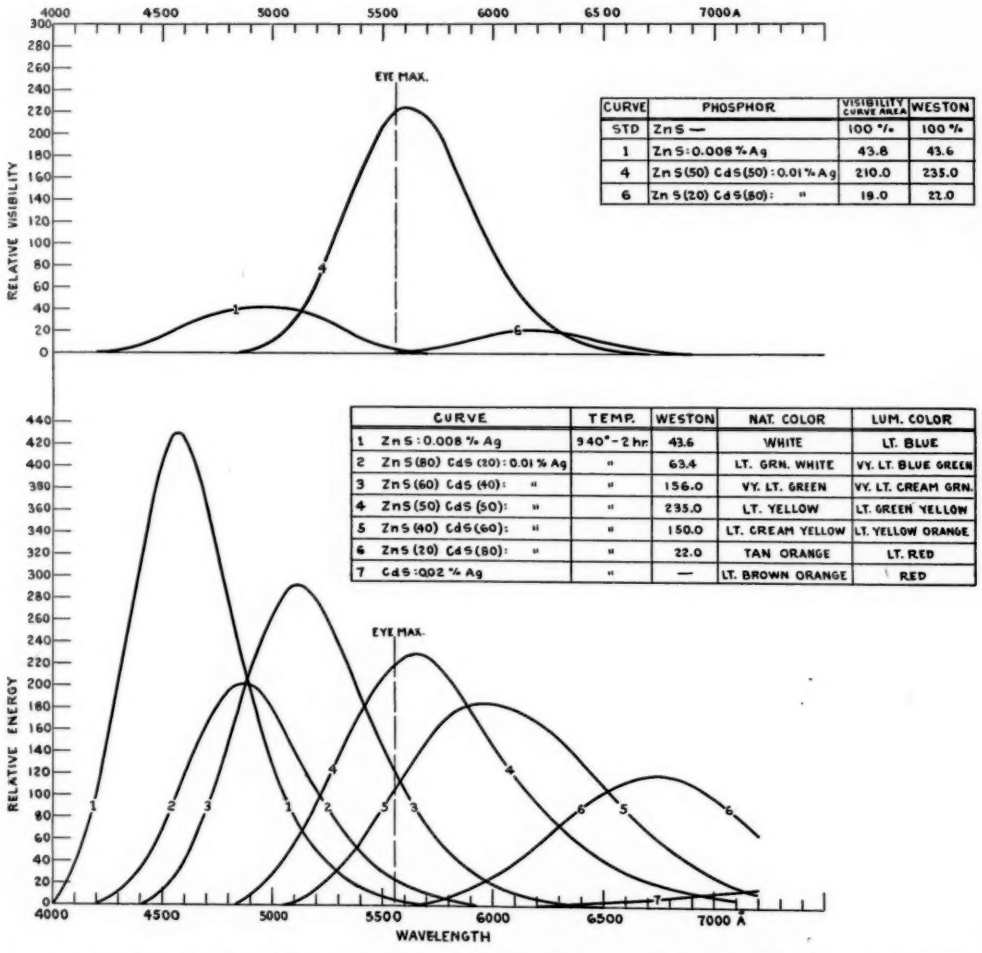

4000
4500
5000
5500
6000
6500
7000A
EYE MAX.
RELATIVE VISIBILITY
CURVE | PHOSPHOR | VISIBILITY CURVE AREA | WESTON
STD | ZnS — | 100 % | 100 %
1 | ZnS:0.008 % Ag | 43.8 | 43.6
4 | ZnS(50) CdS(50):0.01 % Ag | 210.0 | 235.0
6 | ZnS(20) CdS(80): " | 19.0 | 22.0
CURVE | TEMP. | WESTON | NAT. COLOR | LUM. COLOR
1 ZnS:0.008 % Ag | 940°-2 hr | 43.6 | WHITE | LT. BLUE
2 ZnS(80) CdS(20):0.01 % Ag | " | 63.4 | LT. GRN. WHITE | VY. LT. BLUE GREEN
3 ZnS(60) CdS(40): " | " | 156.0 | VY. LT. GREEN | VY. LT. CREAM GRN.
4 ZnS(50) CdS(50): " | " | 235.0 | LT. YELLOW | LT. GREEN YELLOW
5 ZnS(40) CdS(60): " | " | 150.0 | LT. CREAM YELLOW | LT. YELLOW ORANGE
6 ZnS(20) CdS(80): " | " | 22.0 | TAN ORANGE | LT. RED
7 CdS:002 % Ag | " | — | LT. BROWN ORANGE | RED
EYE MAX.
RELATIVE ENERGY
WAVELENGTH
4000
4500
5000
5500
6000
6500
7000 A

FIG. 1. Spectral distributions of energy and visibility of the zinc sulphide-zinc cadmium sulphide phosphor system.

is shown, but details of the automatic recording spectroradiometer[4] are omitted. The actual absorption curves are obtained as deviations from the known energy distribution of a calibrated incandescent lamp. It is seen that short wave visible radiation excites considerable luminescence in the zinc-cadmium sulphides, as evidenced by the dotted curves of emission above the zero axis of Fig. 2. Inspection of the absorption curves of Fig. 2 shows how strongly the yellow, orange, and red phosphors absorb blue and green light. A mechanical mixture of blue and yellow sulphides, calculated simply upon their known relative spectral distributions, would not yield an additive resultant emission spectrum, but would be deficient in the blue because of the yellow component's blue-absorption. The selective absorption effect may be avoided by depositing the phosphor crystals in separate layers such that the strongly-absorbing phosphors are on the side of the screen opposite the observer or projection lens.

Given a practically unlimited choice of well-saturated hues, and assuming equal efficiency of energy emission over the entire visible spectrum, there is the question as to which pair of the many

[4] V. K. Zworykin, J. Opt. Soc. Am. **29**, 84–91 (1939).

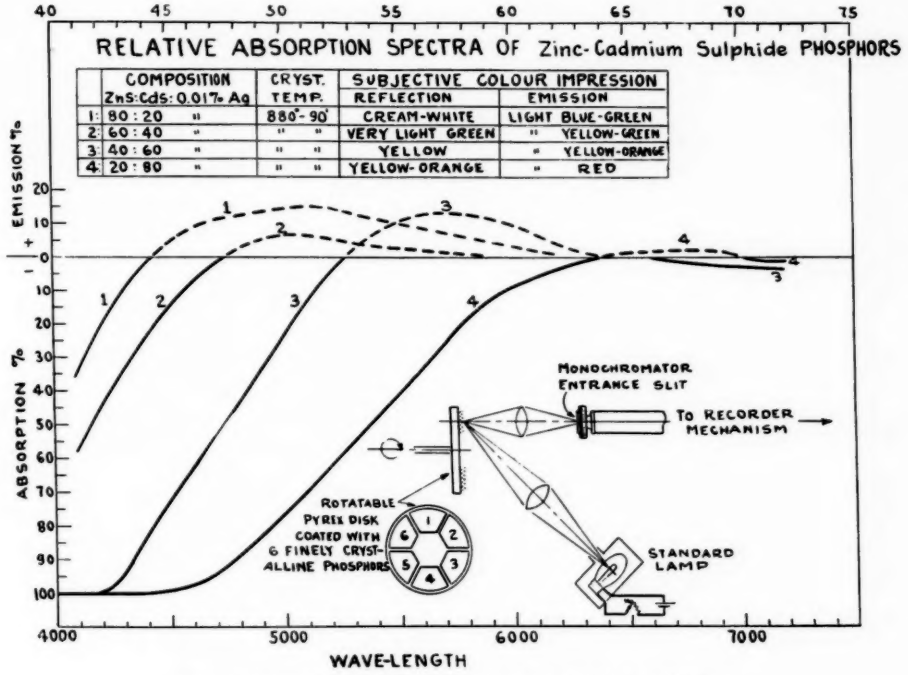

RELATIVE ABSORPTION SPECTRA OF Zinc-Cadmium Sulphide PHOSPHORS
COMPOSITION ZnS:CdS: 0.01% Ag
CRYST. TEMP.
SUBJECTIVE COLOUR IMPRESSION
REFLECTION
EMISSION
1: 80 : 20 " 880°-90° CREAM-WHITE LIGHT BLUE-GREEN
2: 60 : 40 " " " VERY LIGHT GREEN " YELLOW-GREEN
3: 40 : 60 " " " YELLOW " YELLOW-ORANGE
4: 20 : 80 " " " YELLOW-ORANGE " RED
EMISSION %
ABSORPTION %
MONOCHROMATOR ENTRANCE SLIT
TO RECORDER MECHANISM
ROTATABLE PYREX DISK COATED WITH 6 FINELY CRYSTALLINE PHOSPHORS
STANDARD LAMP
WAVE-LENGTH

FIG. 2. Absorption spectra of zinc cadmium sulphide phosphors.

complementary colors will give optimum visible efficiency of white light.

Table I[5] shows some complementary monochromatic wave-lengths, λ_1 and λ_2, their individual relative luminosities (L_λ) interpolated from eye visibility data (see curve, Fig. 4) and the paired relative luminosities (L) of each complementary wave-length required to produce the sensation of white at 75 photons ($=L_1+L_2$). (One photon = unit of visual stimulation = surface brightness of one candle/meter^2 (0.2914 foot-lambert) seen through a pupil of 1 mm^2 area.) The value of 75 photons expressed in foot-lamberts is: $75\times0.2914=21.9$ foot-lamberts. This value is near enough to the 18-foot-lambert[6] highlight brilliance of a 12-inch kinescope screen to allow direct use of the luminosity data for conclusions concerning cathode-ray television images.

TABLE I. *Complementary wave-lengths and their relative luminosities.*

Complementaries					Relative Luminosities		Relative Luminosities of λ_1 and λ_2 Which, When Added, Produce White		
Pair No.	λ_1	Hue λ_1	λ_2	Hue λ_2	$L\lambda_1$	$L\lambda_2$	L_1	L_2	L_2/L_1
1	4430 A	Violet-Blue	5705 A		0.0275	0.9479	1.8	73.2	40.6
2	4590		5720	Yellow-Green	0.0578	0.9356	2.9	72.1	24.9
3	4665	Blue	5730		0.0802	0.9274	4.4	70.6	16.0
4	4720		5740		0.1006	0.9192	6.0	69.0	11.5
5	4745		5755		0.1126	0.9069	7.3	67.7	9.3
6	4775	Green-Blue	5765	Yellow	0.1270	0.8087	9.2	65.8	7.16
7	4805		5785		0.1425	0.8823	10.8	64.2	5.95
8	4825		5800	Orange-Yellow	0.1563	0.8700	13.0	62.0	4.77
9	4875		5860		0.1908	0.8012	19.6	55.4	2.82
10	4900	Blue-Green	5910	Orange	0.2080	0.7444	24.7	50.3	2.04
11	4935		6090	Red-Orange	0.2483	0.5158	35.7	39.3	1.10
12	4960		6500		0.2770	0.1070	43.4	31.6	0.73

The solid curve of Fig. 3 shows the complementary color relationship expressed in graphical form, with the green-blue wave-length scale on the ordinate and the yellow-red wave-length scale on the abscissa to give the complementary intercepts from any point on the solid curve.

[5] R. H. Sinden, J. Opt. Soc. Am. and Rev. Sci Inst. **7**, 1123–1153 (1923).

[6] V. K. Zworykin and W. H. Painter, Proc. I. R. E. **25**, 937–953 (1937).

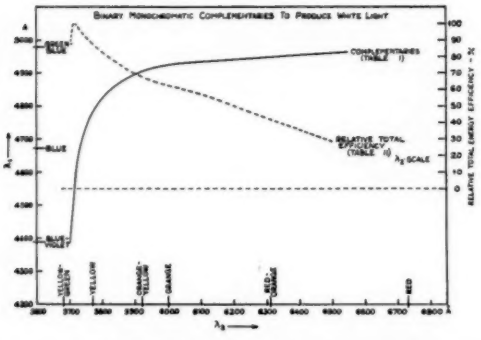


FIG. 3. Graphical representation of complementary wave-lengths and their efficiencies.

From the relative luminosity data in Table I, the relative radiant energies (E_λ) required to produce white light from the listed complementaries are calculated and listed in Table II.

By forming the quotients of the paired relative luminosities L_1 and L_2 of each complementary wave-length with their corresponding individual relative luminosities, L_{λ_1} and L_{λ_2}, we obtain the expressions

$$E_{\lambda_1}=L_1/L_{\lambda_1} \quad \text{and} \quad E_{\lambda_2}=L_2/L_{\lambda_2}.$$

These give the relative energies of the given complementary wave-lengths, λ_1 and λ_2, required to produce 75 photons of white light. For example, with complementary pair 5, the relative energies required at each of the two wave-lengths, 4745A and 5755A, in order to give 75 photons of white light are

$$E_{4745}=7.3/0.1126=64.9$$

and

$$E_{5755}=67.7/0.9069=74.7.$$

The total energy required to produce white light from any complementary pair is

$$E_T=E_{\lambda_1}+E_{\lambda_2}$$

and the relative percentage of the total energy contributed by each wave-length, λ_1 and λ_2, comprising a white light complementary pair is given by

$$E_1=E_{\lambda_1}/E_T$$

and

$$E_2=E_{\lambda_2}/E_T.$$

For example, from a continuation of the analysis of pair 5, we obtain

$$E_T=64.9+74.7=139.6,$$
$$E_{1(4745)}=64.9/139.6=46.5\%,$$
$$E_{2(5755)}=74.7/139.6=50.6\%.$$

The values E_1 and E_2 give the percentages of the total radiant energy E_T which must be produced at the given wave-lengths, λ_1 and λ_2, to produce 75 photons of white light.

In the last column of Table II, the total energy values E_T are reduced to efficiency percentage values in terms of the most efficient complementary pair which happens to be pair 2 ($=E_T$ minimum). It is seen that pair 5, of the calculated example, has an efficiency of only 91.3 percent of pair 2, while pair 12 (4960A+6500A) has a white-light producing efficiency of only 28.2 percent. Reciprocally expressed, pairs 5 and 12 would require, respectively, 10 percent and 350 percent more energy expenditure than pair 2 in order to produce equivalent sensations of white light. The relative-energy efficiency data in the last column of Table II are plotted as the

TABLE II. *Complementary wave-lengths and their efficiencies calculated from data of Table I.*

Pair No.	Complementaries		Relative Energies Required to Produce White Light		Total Energy $E_{\lambda_1}+E_{\lambda_2}=E_T$ (75 Photons)	Relative Percentage of Total Energy		Relative Energy Efficiency $E_{T\min}/E_T$
	λ_1	λ_2	E_{λ_1}	E_{λ_2}		E_1	E_2	
1	4430	5705	65.5	77.3	142.8	45.9%	54.1%	89.3%
2	4590	5720	50.2	77.1	127.3	39.5	60.5	100. (Arb. Std.)
3	4665	5730	54.8	76.3	131.1	41.8	58.2	97.1
4	4720	5740	60.0	75.2	135.2	44.4	55.6	94.2
5	4745	5755	64.9	74.7	139.6	46.5	53.5	91.3
6	4775	5765	72.5	74.4	146.9	49.4	50.6	86.8
7	4805	5785	75.8	72.8	148.6	51.0	49.0	85.8
8	4825	5800	83.2	71.3	154.5	53.9	46.1	82.5
9	4875	5860	102.8	69.2	172.0	59.8	40.2	74.0
10	4900	5910	118.8	67.6	186.4	63.8	36.2	68.4
11	4935	6090	143.7	76.2	219.9	65.5	34.5	57.9
12	4960	6500	156.6	295.0	451.6	34.7	65.3	28.2

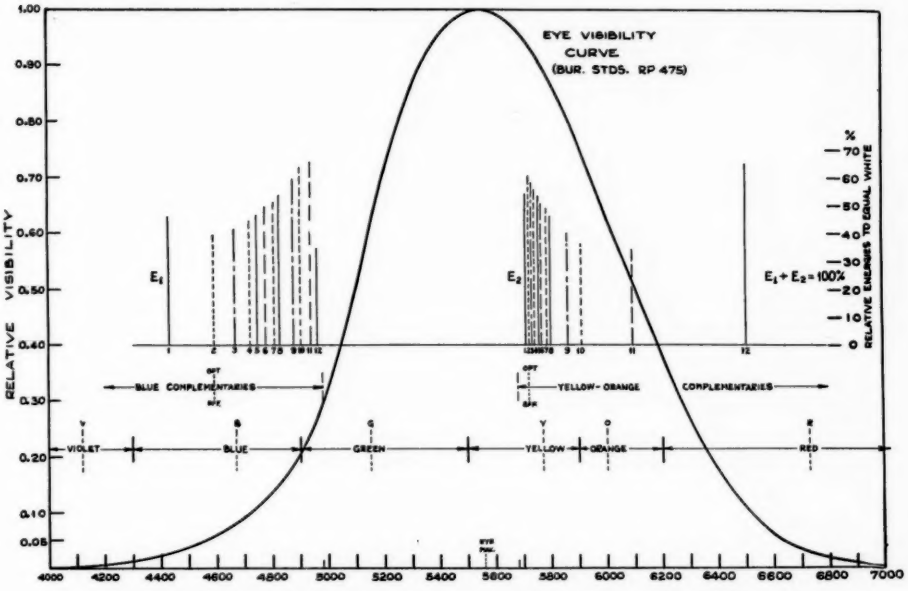


FIG. 4. Eye sensitivity curve and the energy ratios of spectral complementaries.

dotted curve corresponding to the right-hand ordinate scale in Fig. 3. From the maximum of the sharply peaked curve, it is concluded that the most efficient, binary-monochromatic-white-producing source comprises violet-blue light (4590A) and green-yellow light (5720A).

Figure 4 shows the eye visibility curve, the approximate color zones and the relative energies (E_1 and E_2 from Table II) required to produce 75 photons of white light. The heights of the vertical lines of E_1 and E_2 are in direct proportion to the numerical values of E_1 and E_2 and may be read from the percentage scale on the right-side ordinate. It is noticeable that the values of E_2, discounting pair 12 which is very unfavorably located with respect to the visibility curve, rise to a maximum at pair 2 which is quite close (93.6 percent) to the maximum sensitivity of the human eye. The value of E_1 for optimum efficiency should naturally be kept to a minimum since none of the blue complementaries has a relative luminosity higher than 28 percent of the eye maximum. The maxima and minima of the families of E_1 and E_2 lines are in reciprocal relationship since $E_1+E_2=100$ percent.

For practical purposes, the monochromatic wave-lengths given in the tables may be translated into narrow-band spectra since the fusion mechanism of color vision cannot separate the individual components of a composite color. Each wave-length thus represents any band spectrum giving substantially the same saturated color. Most of the efficient phosphors have rather narrow emission bands which are symmetrical enough to be treated as the colors represented by the maxima of their spectral-distribution curves.

The practical conclusion from the above analysis is that a violet-blue-emitting phosphor, such as silver-activated zinc sulphide (band centered around 4590A) mixed with a substantially equivalent particle-size green-yellow-emitting phosphor such as zinc beryllium silicate or zinc-cadmium sulphide (band centered around 5720A) should be used to obtain optimum efficiency. A third, *viz.* green, component may be used to balance irregularities in band shapes.

Although this conclusion was not previously obvious, being obscured by inadequate knowledge of the energy economics of complementary color-mixing and the misleading fact that light blue (unactivated) sulphides give 2–3 times the visual efficiency of the recommended violet-blue-emitting, silver-activated zinc sulphide, it is apparent that the luminescent materials further

assist this analysis, since the blue zinc sulphides, yellow zinc beryllium silicates, and yellow zinc cadmium sulphides have increasing peak energy output as their spectra are shifted to shorter wave-lengths (Fig. 1 and reference 2). A further advantage is obtained in reducing the action of yellow zinc-cadmium sulphides which have strong absorptions of blue light in proportion to the extension of the yellow sulphide's emission maximum toward the red (Fig. 2). By keeping the cadmium sulphide content as low as possible, the blue-light absorption is minimized. Yellow-emitting zinc-beryllium silicates have practically negligible absorption in the visible region.

Another point of practical interest is the critical nature of color mixing in the yellow-component region from 5705–5800A, corresponding to an equivalent complementary range four times as broad (4430–4825A) in the blue region as shown in Fig. 4. The use of a small percentage of a third component, such as green or orange, sometimes helps to effect production of a good white light without the need of using complementary luminescent materials in exactly matched pairs.

The addition of more emitted energy in the violet and red, in order to produce equal energy over the entire visible spectrum is useful to provide a uniform, continuous source of radiant energy for many experiments in physical optics. In fact, the production of almost any band-spectrum color is much more feasible using the controllable phosphor-spectrum shifting-means already demonstrated, than is true for the "hit or miss" method of filtering white light sources with the usual absorbing media which do not allow convenient gradual spectral variation.

Figure 5 shows the emission spectra of two white-emitting mixed-phosphor kinescope screens. Screen (a) is composed of zinc sulphide plus zinc beryllium silicate and screen (b) is entirely sulphide phosphors. A comparison of the blue ends of the two curves shows the pronounced blue absorption of the yellow-emitting zinc cadmium sulphide (curve b).

The white screens shown in Fig. 5 are nearly a "daylight" (i.e., bluish-) white. It may well be that television screens should not be too close an approximation to either incandescent lamp-, reddish-white or to daylight-, bluish-white, since it is desirable to operate television receivers in partially lighted rooms. Many television engineers prefer more saturated kinescope emission colors, such as yellow or green, in order to have good halftones in the television image without decreasing the usual illumination in the room and in order to have optimum luminescence efficiency by virtue of the phosphor's close approximation to the eye sensitivity curve.

Crystalline luminescent materials are now to be numbered among the more useful light sources, possessing good brilliancy (over 1,400,000 foot-lamberts for a short time when excited by 70,000-volt electrons[7]), high energy-conversion efficiency (up to 80 percent when some materials are excited by monochromatic ultraviolet[8]) and permitting unequaled degree of convenient con-

[7] K. Scherer and R. Rübsaat, Archiv. f. Elektrotech. 31, 821–826 (1937).
[8] A. Rüttenauer, Zeits. f. tech. Physik 5, 148–150 (1938).

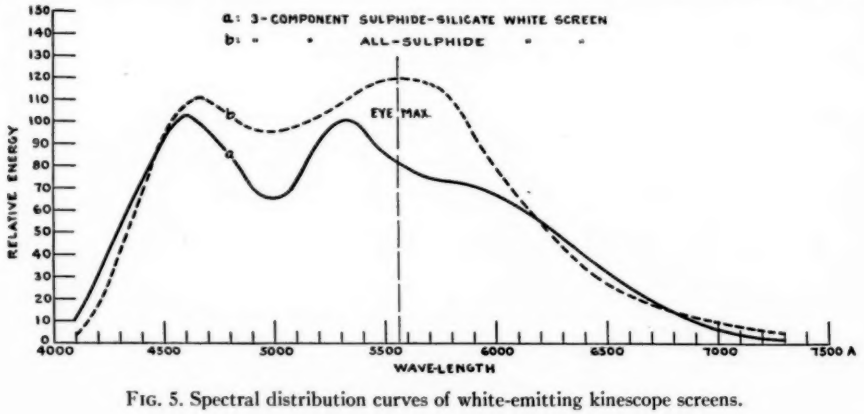


FIG. 5. Spectral distribution curves of white-emitting kinescope screens.

trol of color hue and saturation. Future uses will certainly see the extension of phosphor applications in the ultraviolet and infra-red regions of the spectrum when the important qualities of luminescent materials as unique transformers of both radiant and corpuscular energies are further exploited.

Although a quantitative theoretical treatment of phosphor luminescence is not yet developed, cross-references with associated effects such as the photoelectric effect, secondary electron emission, dielectric and semiconducting properties of crystals have indicated that the best phosphors have a bulk crystal which is of the excess cation type of semiconductor and contains a very small amount of some multivalent metallic element as an activator. Furthermore, the activator should be approximately the same size as the cation of the bulk crystal.

In closing, it is significant to note that cathodo-luminescence should probably be classified as a general property of solid matter—not just a phenomenon observed in isolated cases. Over 6000 widely different solid substances and materials, both vitreous and crystalline, having widely varied degrees of purity or impurity have been synthesized and tested in our laboratories. Every one of these materials showed discernible luminescence under electron bombardment. This was true even when the natural reflection color of the material under white light was definitely black. It is likely that *really* perfect crystals of some *really* pure substances would not luminesce in the visible spectrum, but we have not been able to obtain or synthesize such specimens despite the use of specially constructed equipment in a unique air-conditioned luminescence, research laboratory.

Acknowledgment is made of the work of Mr. E. J. Wood who accomplished most of the syntheses of the sulphide phosphors described in this paper and reference 2.

Election of Officers

THE following officers have been elected by the Rochester Section of the Optical Society of America to serve during the year 1940–41:

President: Brian O'Brien
Vice President: R. Bruce Horsfall, Jr.
Secretary: David L. MacAdam
Treasurer: John W. Gillon
Council: Henry F. Kurtz
John H. McLeod
Cyril J. Staud
T. Russell Wilkins
Robert E. Burroughs (*ex officio*)

Research Notes

Note on the Measurement of Pupillary Diameters*

In a recent issue of this journal,[1] R. Clark Jones described an instrument, the koremetron, for measuring pupillary diameters. This instrument essentially consists of a lens of short focal length and a screen suitably placed in front of the eye. In the optical system lens and eye, the image of the iris diaphragm of the eye in object space is the entrance pupil.[2] Since a change in pupillary diameter affects the field of view, one has a means of measuring the diameter of the iris.

It is possible to make similar measurements without the use of a lens in the following way. In Fig. 1, I, P and S represent the image of the iris diaphragm in object space, a pinhole and a diffusely illuminated screen, respectively. I is close to the actual position of the iris diaphragm because according to Southall,[3] who employed the data of Gullstrand's schematic eye, the image of the iris diaphragm in object space is about 0.6 mm nearer the vertex of the cornea than the iris diaphragm itself. The lines drawn show the maximum field of view in object space. In this system, P is the entrance pupil and I the entrance window, for screens S that are not too close to the eye. If there is a change in the diameter of the iris diaphragm, there is a corresponding change in the diameter of the entrance window which affects the field of view in the object space. Thus, if the eye is constantly accommodated for a suitably constructed screen, it is possible to make measurements.

If R, R_1 and R_2 are the radii of the image of the iris diaphragm in object space, the pinhole and the circular portion of the screen that is seen illuminated, respectively, then

$$R=(R_2-R_1)d/D-R_1,$$

where d and D are the distances of I and S from the pinhole. Since the radius of the iris diaphragm, let us say r, is proportional to the radius of its image in object space, it is possible to determine the relative changes in r without a knowledge of the distance d. If the absolute value of r is desired, it would be necessary to determine the constants of each subject's eye. However, the phenomenon of diffraction as well as the manner in which the light intensity decreases toward the periphery of the field of view even according to geometrical optics, would make precise measurements of r difficult.

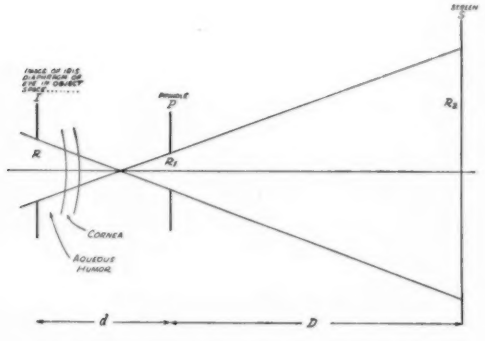


FIG. 1. Schematic diagram of eye viewing screen through a pinhole.

Although the experiments performed by the author and by others were rather crude, the changes produced in various ways in the pupil of either eye were readily observed. It should be a relatively simple matter to construct an apparatus along the lines described.

The author wishes to thank Professor A. G. Shenstone for his helpful criticism.

ROBERT C. HERMAN

Palmer Physical Laboratory,
Princeton University,
Princeton, New Jersey,
February 9, 1940.

[1] R. Clark Jones, J. Opt. Soc. Am. **29**, 531 (1939).
[2] The terminology employed is that of Hardy and Perrin, *The Principles of Optics* (McGraw-Hill, 1932).
[3] J. P. C. Southall, *Mirrors, Prisms and Lenses* (MacMillan, 1936).

On the Use of Oiled Photographic Emulsions*

OILS of various kinds, such as motor oils, kerosenes, and paraffin oils, have long been used on photographic emulsions for fluorescent sensitization to light and to charged particles, and for providing mechanical or optical contact or both between emulsions and other bodies. After exposure and before development, it has been customary to remove such oils by bathing or washing the emulsions with acetone[1]—unless quite volatile oils were used, in which cases simple evaporation sufficed to remove them.

It is the purpose of this note to call attention to the usefulness of two other very convenient solvents for removing oils: petroleum ether (benzine) and carbon tetrachloride (CCl_4). These substances evaporate[2] readily and thus allow very quick cleaning operations. They are usually somewhat less expensive than acetone. Carbon tetrachloride has the advantage of being fireproof, while petroleum ether has the advantage of being nearly chemically homologous with the strongly fluorescent commercial motor oils now available.

We have made tests which indicate that neither of these two solvents, petroleum ether and carbon tetrachloride, is appreciably harmful to the ordinary emulsions when used to remove such oils as those mentioned above.

F. T. ROGERS, JR.

The W. J. McDonald Observatory,
The University of Texas,
Fort Davis, Texas,
December 28, 1939.

* We wish to acknowledge our pleasant discussion of this topic with Dr. Eby Nell McElrath of The University of Houston.
[1] See, e.g., J. Strong's *Procedures in Experimental Physics* (Prentice-Hall, 1938), p. 462.
[2] E.g., J. T. Baker and Company has at present two commercially available petroleum ethers. One boils in the temperature range of 35°–60°C, while the other boils at 20°–40°C.

Necrology

Edward Elway Free

EDWARD ELWAY FREE, consulting physicist and chemist, died on November 24, 1939 at Post Graduate Hospital, New York City, due to post-operative complications following a short illness. He was 56 years old.

Dr. Free was born at Dagus Mines, Pennsylvania, on May 3, 1883. He graduated from Bellefonte (Pennsylvania) Academy in 1902 and received his A.B. degree from Cornell University in 1906 and his Ph.D. degree from Johns Hopkins University in 1917.

From 1906 to 1907 he was assistant chemist at the Agricultural Experiment Station at the University of Arizona and for the next five years was physicist and scientist for the U. S. Department of Agriculture in Washington, D. C. As a consulting chemist and physicist he headed the E. E. Free Laboratories located at 175 Fifth Avenue, New York City, since 1912. During the World War he served as captain in the Ordinance Department and as major with the Chemical Warfare Service, having seen service overseas.

From 1924 to 1925 he was editor of the *Scientific American* and was owner and editor of *The Week's Science* (a news service) started in 1926. He was a regular contributor of scientific editorials to the *New York Herald Tribune*, as well as to many other publications.

From 1926 to 1934 he was a lecturer at New York University, heading the course in Outlines of Science given at the School of Commerce, Accounts and Finance.

He was a former president of the New York Electrical Society and treasurer of the Acoustical Society of America. He had been a member of the Optical Society of America since January 9, 1936.

ADELE FRANK

Harold Mestre

THE death of HAROLD MESTRE last September at the early age of 55 abruptly removed a colorful personality from the scientific scene. Mestre's career was a varied and interesting one. He was born in Mamaroneck, New York, August 16, 1884. After St. Paul's School he entered Columbia to study engineering, but left college before completing his course. For a while he was a stock broker in New York, after which he became a safety engineer in San Francisco and was engineering consultant to the California Welfare Commission.

It was after the first World War that Mestre decided on an academic future and again entered college. He received a B.A. from California in 1923 and immediately joined the faculty of the State Teachers College in Fresno where he taught from 1924 to 1927. In 1929 he received a Ph.D. from Stanford, and remained on the faculty of Stanford until 1933, his connection being mainly with the Hopkins Marine Station at Pacific Grove. In 1933 he came east and was a Fellow at the Medical School at Yale for a year.

Mestre really found his proper sphere in 1937, when he joined the faculty of Bard College as Associate Professor of Biophysics. He became the Director of Studies almost immediately, and in June, 1938, he became Dean of the College. During this time he took a prominent part in reorganizing the College finances and in developing its new program of instruction. He was obviously in his element in this work, and his death was a setback to the College at a critical period in its growth.

Mestre's scientific interests lay between physics and biology. His first researches were on photosynthesis. This broadened out to a study of related pigments present in plants. He started an investigation of the penetration of light in sea water, and built a photoelectric device for the quantitative determination of some elements in sea water based on the formation of colored compounds. This research grew into an elaborate theoretical and experimental study of the scattering of radiation by suspensions of cells, and resulted in the development of a photoelectric apparatus for the determination of the density of bacterial suspensions.

Only a small fraction of his work has been published. Essentially Mestre was a perfectionist. He felt that many physical methods for the determination of biological function were either obviously inaccurate or contained theoretical inadequacies which might vitiate their meaning. He granted that science progresses in a series of approximations. Nevertheless, the perfectionist position demanded that his own research be done so that no criticism could be leveled against its method. As compensation, this attitude together with his unfailing enthusiasm served to stimulate students and associates. His wit and good nature were well known and made him many friends and admirers.

SELIG HECHT

Carl F. Lomb

CARL F. LOMB, Vice President of the Bausch & Lomb Optical Company, passed away at his home in Rochester on Thursday, January 26, 1939.

Born in Birstein, Hesse Cassel, Germany, May 31, 1854, Mr. Lomb came to the United States in 1873 and was admitted to citizenship in 1879. He was first associated with the banking house of Jay Cooke & Company, of New York City, and later joined the First National Bank of New York.

In 1874, Mr. Lomb became associated with the New York Office of Bausch & Lomb Optical Company. In 1875 he came to Rochester to aid in the formation of the Rochester German Insurance Company. He returned to his work with Bausch & Lomb in 1877 where his training in accountancy and finance brought him continuous advancement. In 1882, he was elected secretary of the company and in 1909 was made a Vice President, a position he

held continuously thereafter. In addition to his association with Bausch & Lomb, Mr. Lomb served as vice president of Yawman & Erbe Manufacturing Company, trustee of the Security Trust Company and director of the Rochester Telephone Corporation.

Like his illustrious cousin, Captain Henry Lomb, Mr. Lomb was not content with a life solely devoted to business achievement. His youth and all his native interests gave him an intuitive insight into the needs of young people. Rochester Athenaeum and Mechanics Institute, whose lectures he attended as a young man, became the natural medium for the expression of his interest. In 1910, he was elected to the Board of Directors and in 1916 became its President. Subsequently, Mr. Lomb was made Chairman of the Board, a position he held continuously until his death.

Mr. Lomb was very active in the period of adjustment of the Institute, following the loss of such leaders as Captain Henry Lomb, Ezra R. Andrews and Lewis P. Ross. Educational requirements in Western New York were changing rapidly and the Board was confronted with demands for teachers of applied arts, home economics, and manual training. Rapid changes were brought about by post-war rehabilitation problems and the continuous expansion of the Institute's educational program.

To these problems Carl Lomb brought the energy, sincerity and ability with which he had achieved an enviable position as a leader in the industrial life of Rochester.

Mr. Lomb took a keen interest in civic affairs and good citizenship. He was one of the organizers of the Better Citizen Council of the Rochester Chamber of Commerce and served as chairman of this group for a period of time.

One of Mr. Lomb's happiest experiences occurred on July 25, 1930, when, on behalf of the families of John J. Bausch and Captain Henry Lomb, he dedicated the new Physics Building at the University of Rochester, the gift of the families and erected in memory of the founders of the company. He was happy to know that Rochester, his adopted city, and the university would establish the first Institute of Applied Optics in America.

CARL L. BAUSCH

Harold D. Judd

HAROLD D. JUDD was born in Ypsilanti, Michigan in 1888 and died in Detroit on January 1, 1939, after one week's illness, of pneumonia. He worked in chemical investigaton during the war, and had been an optical technician for the Wolverine and Johnston Optical Companies, and associated in that capacity with Doctors Robb and Pino. In 1933 he entered private optometric practice in which he specialized in the corrective treatment of subnormal vision of children, in association with the sight saving classes in the Detroit schools.

Dr. Judd's published work includes studies of the role of defective vision in automobile accidents, an article with G. L. Walls, then at the University of Michigan, on the color filters in the eyes of vertebrates, work on the localization of lesions producing visual field defects, and papers on the teaching of orthoptics and on the interpretation of the retinal image. Before his death he was making, with Dr. E. H. Arnold of Ann Arbor, some important studies of blur points and their interpretation in ocular correction. He was known as a skilful microscopist and physiologist.

Dr. Judd studied at the Ypsilanti Teachers' College, the Detroit Institute of Technology, and elsewhere, and held the A.B. and M.Sc. degrees, as well as others conferred for work in his special fields. He was a member of many societies, including the A.A.A.S., the Optical Society of America, and the American Optometric Association and was active in the scientific and social organizations of his community. It would be hard to find a more active and useful career, and Dr. Judd's life was cut off when it promised to be more useful.

W. W. SLEATOR

Jonas Bernard Nathanson

J. B. NATHANSON died suddenly on November 25, 1939. He had passed his fiftieth birthday only two months before. He was born in Vilna, Lithuania, and came to this country in his early youth. He received his secondary school education at Toledo, Ohio. His undergraduate college work was taken at Ohio State University, where he received his A.B. degree in 1912. At the University of Illinois he received his A.M. degree in 1913 and Ph.D. degree in 1916. While at Illinois he also served as an assistant in physics. Upon leaving Illinois he went to the Carnegie Institute of Technology, where he remained until his death, his position at that time being Associate Professor of Physics.

Dr. Nathanson's research interests were largely devoted to the optics of metals. In the last edition of the American Men of Science he explicitly refers to this subject as his special field, listing in particular "optical properties of alkali metals; ratio of charge to mass of the electron; interference in metallic films; optical dispersion of metals." He published a number of papers on these problems, and was recognized as one of the leading authorities in this field.

He participated actively in professional scientific activities, both local and national. He was a member of Phi Beta Kappa, Sigma Xi, Phi Lambda Upsilon, American Association for the Advancement of Science, American Physical Society, American Association of Physics Teachers, Physical Society of Pittsburgh (President, 1929), and was one of the early members of the Optical Society of America.

Judging by the affection and regard for Dr. Nathanson held by his students, he was a remarkably successful teacher. His personality was such as to inspire confidence and invite cooperation. He was painstaking in the preparation of his lectures to the same extent that he was in the solution of his research problems. Both the Optical Society and the Pittsburgh community have lost a loyal friend, a thorough scholar, and an excellent teacher.

PAUL D. FOOTE

Arthur F. Dittmer

ARTHUR F. DITTMER died at his home in New York City, September 29, 1939.

Dr. Dittmer was born in Ludington, Michigan, August 11, 1900. He was graduated from the University of Michigan in 1923 with an A.B. degree and received his Doctorate degree from Princeton in 1926.

Following his graduation, Dr. Dittmer was a research physicist at Nela Research Laboratories in Cleveland, working on the characteristics of mercury arcs. After leaving Cleveland he served for a year as instructor at the Ohio State University and then became connected with the Technicolor Motion Picture Corporation in Boston. Leaving Technicolor, Dr. Dittmer joined the staff of the Dartmouth Medical School where he was actively engaged in the development of the Ikonic lens. In 1936 he became a member of the Scientific Bureau of the Bausch & Lomb Optical Co. where he worked on the development of contact lenses. In 1938 he left Bausch & Lomb to continue the same work with Optical Research Inc. of New York City.

Dr. Dittmer was a natural experimentalist and his uncanny ability in avoiding difficulties in experimental work made him extremely valuable in his chosen field. In his work the emphasis was always placed on finding practical applications for theoretical facts. Only perfection was satisfactory to him and no project was complete when there was an unanswered question about any stage of the problem.

Dr. Dittmer's death came as a distinct loss to his associates and to all who knew him.

F. W. JOBE

John Stuart Campbell

JOHN STUART CAMPBELL, Assistant Professor of Physical Optics in the University of Rochester, died on September 24, 1939. Dr. Campbell came to the University in 1934 as instructor in Physical Optics, and became an assistant professor in 1938. Although young he had already gained an enviable reputation in the field of spectroscopy before 1934, and in the five years spent at Rochester he continued research in this field, publishing a most noteworthy paper in 1938 on the spectrum of indium in collaboration with Professor Paschen of Berlin. In 1938 he commenced an investigation on the hyperfine structure of spectrum lines, and had already made good progress at the time of his death.

Well trained in other branches of physics, he made many contributions to the discussions and work of the Department of Physics as well as that of Optics. His fine insight into the problems of modern physics rendered his advice and point of view unusually helpful to his colleagues in both departments.

Dr. Campbell's enthusiasm for his chosen field was reflected in his teaching. Aided by a habit of clear thinking and clear expression, he could reduce a difficult problem to its fundamentals and so present it to a class. He was greatly liked and greatly admired by his students, not only for his ability, but for an essential kindliness of character which filtered through in all his contacts.

Those who had the privilege of knowing him well feel his loss keenly, both as a brilliant scientist and as a friend.

BRIAN O'BRIEN